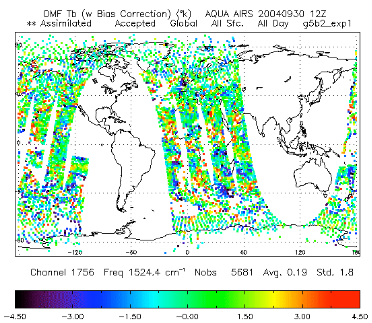
GMAO Satellite Data Assimilation



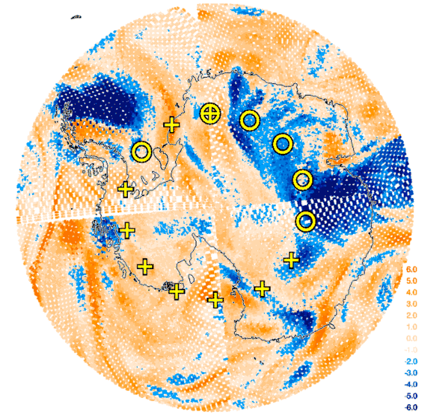
Michele Rienecker

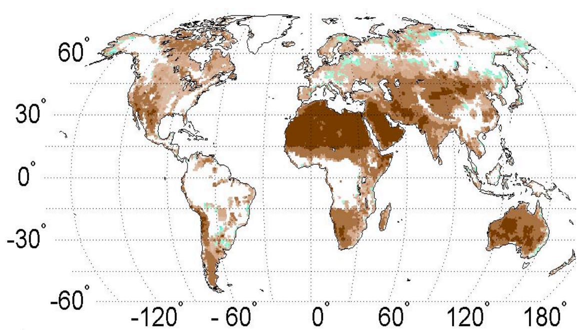
Max Suarez, Ron Gelaro, Ricardo Todling, Emily Liu

Julio Bacmeister, Larry Takacs

Yanqiu Zhu, Ivanka Stajner, Meta Sienkiewicz

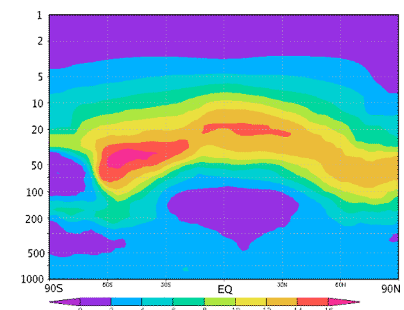
Rolf Reichle, Christian Keppenne

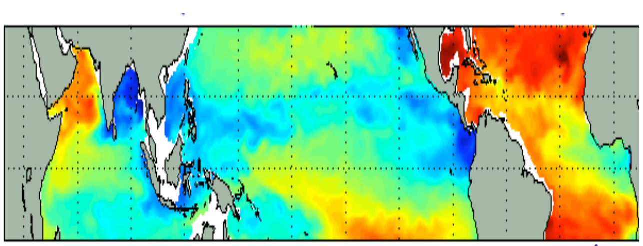


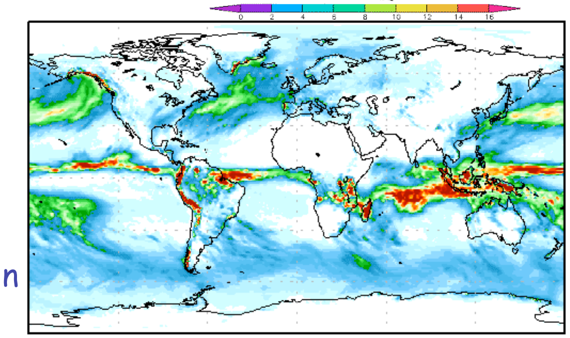


Global Modeling and Assimilation Office (GMAO)

NASA/Goddard Space Flight Center







JCSDA Workshop
Application of Remotely Sensed Observations in Data Assimilation
August 1, 2007

Global Modeling & Assimilation Office

http://gmao.gsfc.nasa.gov

- GEOS-5 Atmospheric Assimilation:
  - NCEP's GSI
  - AIRS
  - Data impacts - Adjoint tools
  - MLS Ozone
  - 4dVAR
- Land Surface: EnKF
- Ocean: EnKF

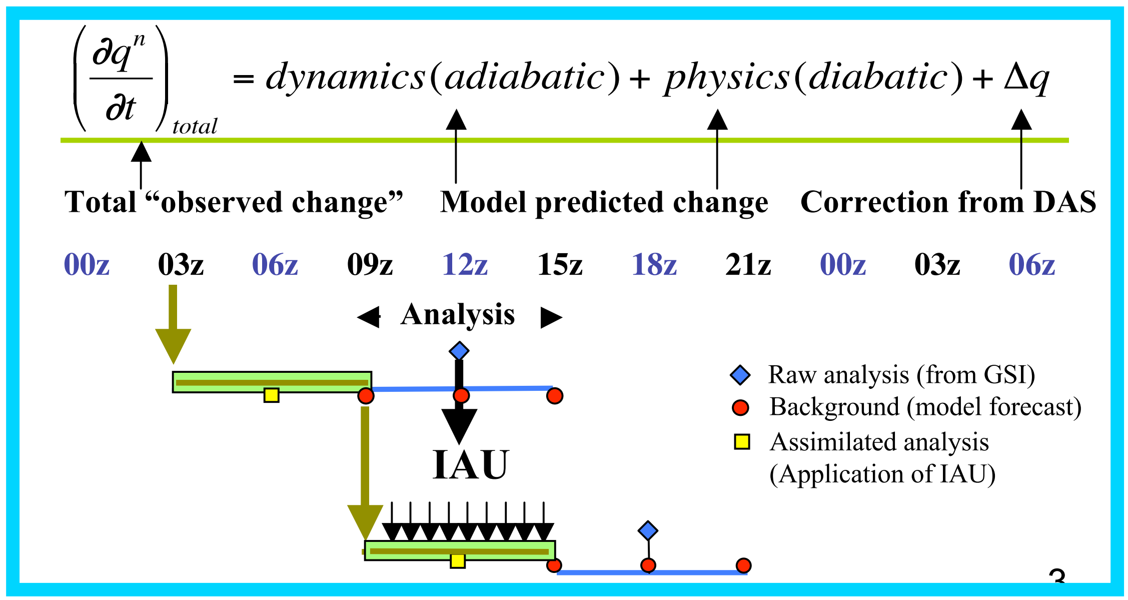
GEOS-5 Atmospheric Data Assimilation System

Ricardo Todling, Max Suarez, Larry Takacs, Emily Liu

- **AGCM**
  - Finite-volume dynamic core
  - Bacmeister moist physics
  - Integrated under the Earth System Modeling Framework (ESMF)
  - Catchment land surface model
  - Prescribed aerosols
  - Interactive ozone

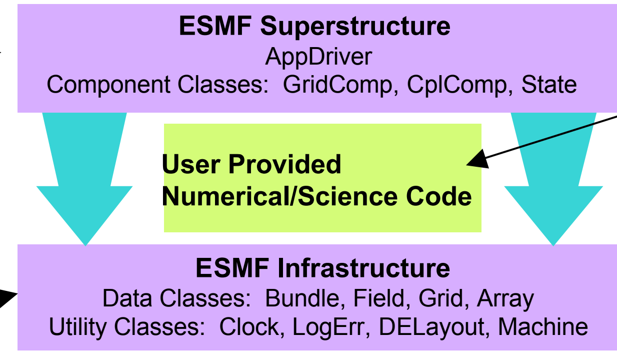
- **Analysis**
  - Grid Point Statistical Interpolation (GSI)
  - Direct assimilation of satellite radiance data
  - JCSDA Community Radiative Transfer Model (CRTM) for most current instruments in space
  - GLATOVS for TOVS (HIRS2, MSU, SSU) on board of TIROS-N, NOAA-06,…, NOAA-12
  - Variational bias correction for radiances

- **Assimilation**
  - Apply Incremental Analysis Increments (IAU) to reduce shock of data insertion
  - IAU gradually forces the model integration throughout the 6 hour period

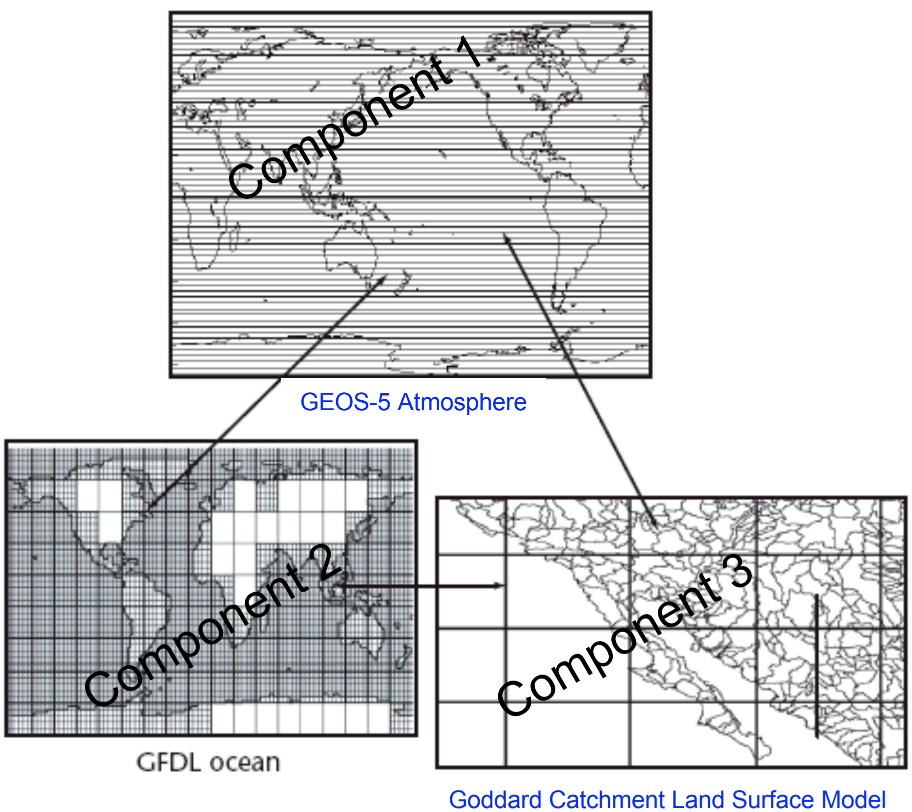


What is ESMF?

- ESMF provides a software library for turning model codes into coupled components with standard interfaces and standard drivers.
- ESMF provides library of common infrastructure that components use for routine services such as data communications, regridding, time management and message



e.g ocean transport, optimization line search, atmospheric radiation.



Example: three model codes operating as coupled components – ESMF provides a parallel, scalable standard software platform to facilitate this coupling, including

• a programming model for coding drivers that steer individual component computations

• data structures for passing information between components

This software is the core of the ESMF component model.

Slide from Chris Hill

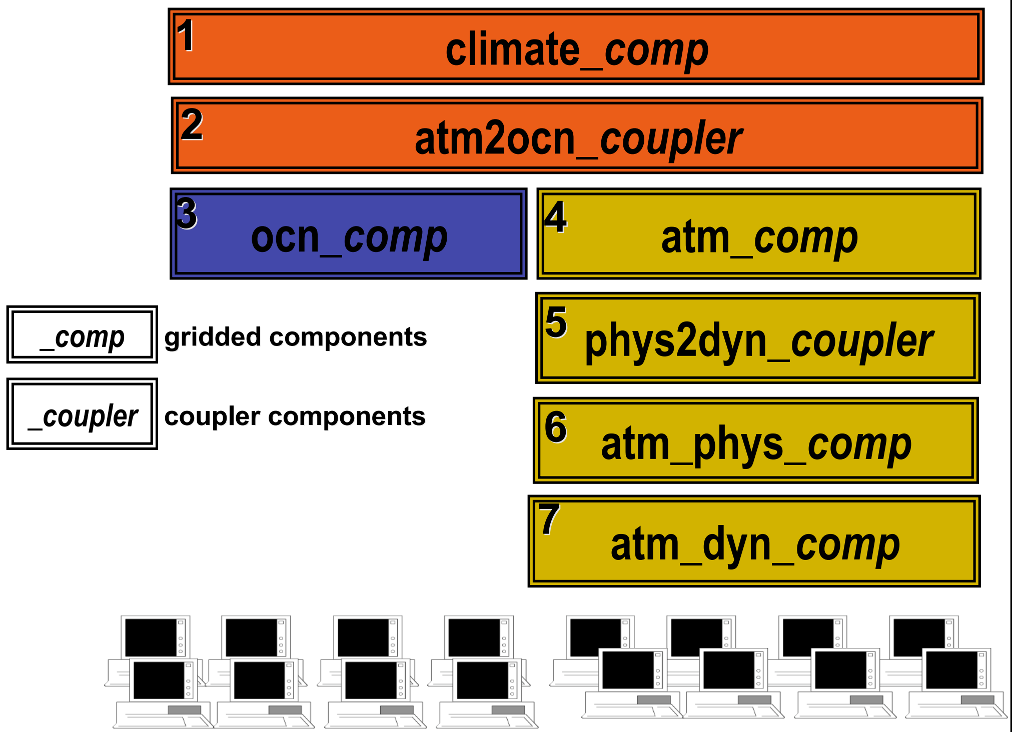
ESMF Component Model

Provides machinery for coding a **hierarchy** of interacting **components**

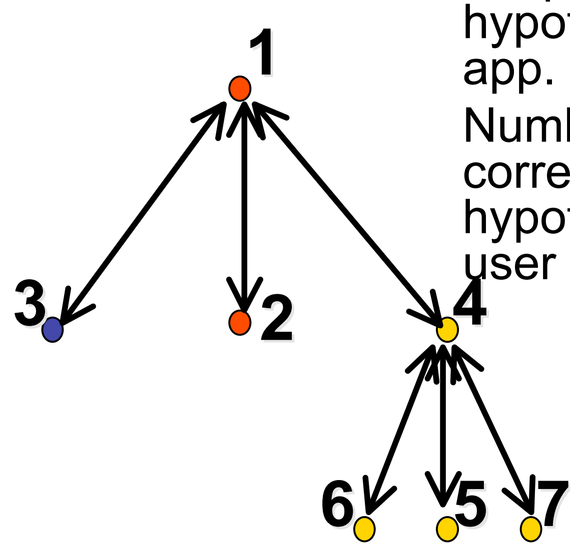
- coupler components, e.g. ocm2atm_*coupler* and
- gridded components, e.g. atm_phys_*comp*

Machinery includes

- general-purpose mechanisms to code “wirings” between components (`ESMF_State`, `ESMF_regrid()`)
- general purpose mechanisms to create components and to control their lifecycle (`SetServices`, `Init()`, `Run()`, `Final()` …)



Hypothetical application on parallel machine

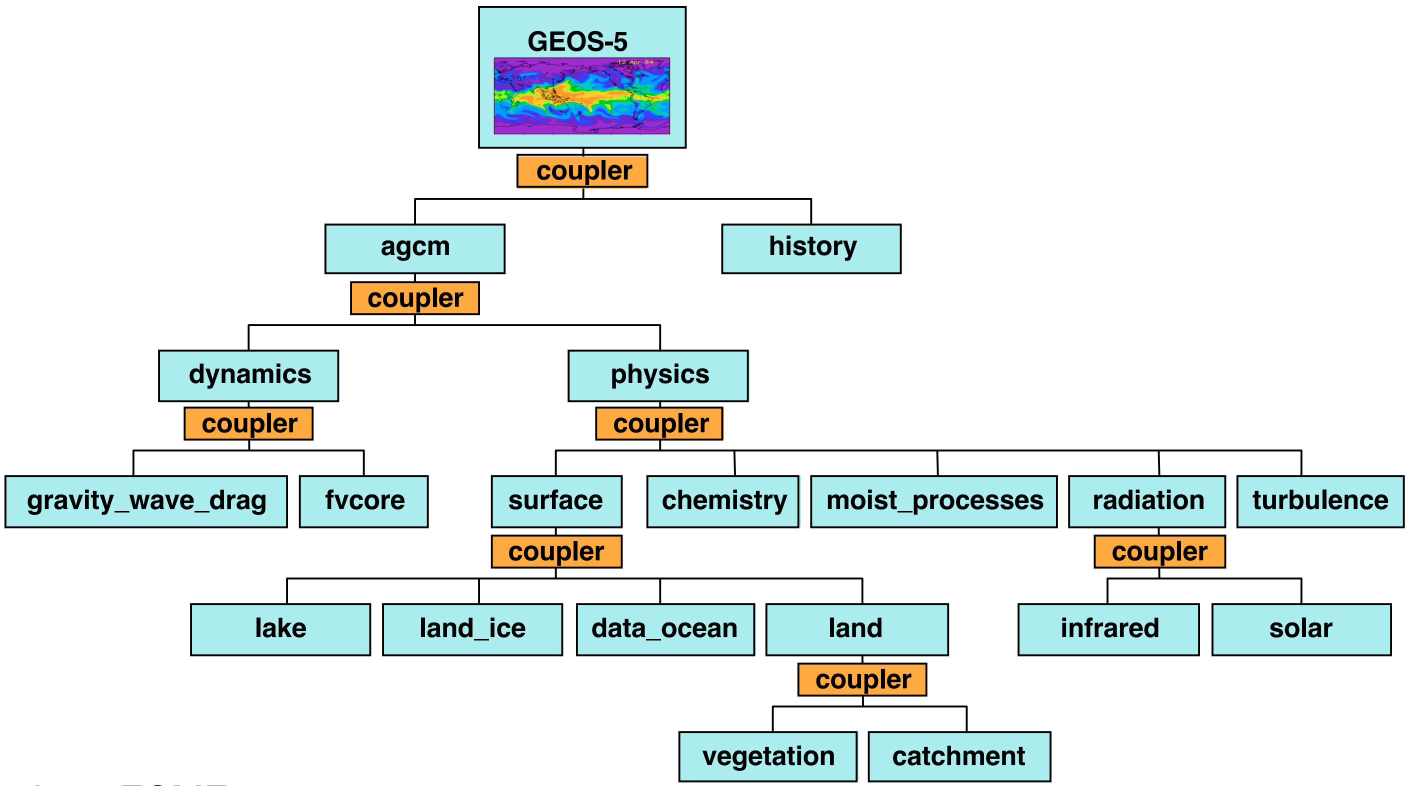


Graph of hypothetical ESMF app. in left panel.

Numbers correspond hypothetical app. user code

Components are nodes . Flow of data between components is shown by edges.

ESMF component graph for GEOS-5 AGCM



- Boxes are user-written ESMF components
- Every component has a standard ESMF interface **`Init()`**, **`Run()`**, **`Finalize()`**. These drive the components.
- Data in and out of components are packaged in **`ESMF_state`** types
- New components can be added to the hierarchical system
- Coupling tools include parallel regridding and redistribution methods

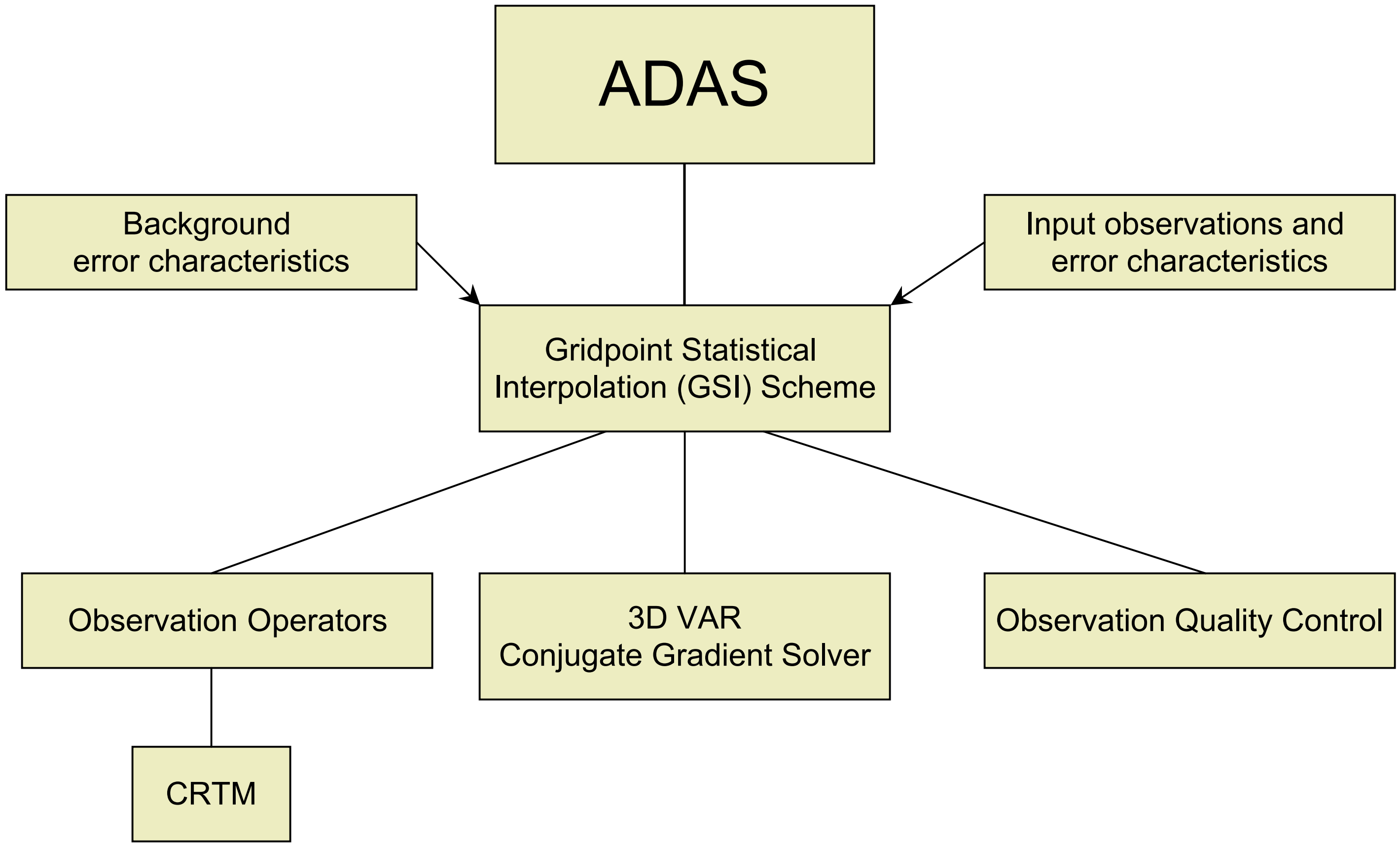
Max Suarez, Atanas Tryanov

More on ESMF:

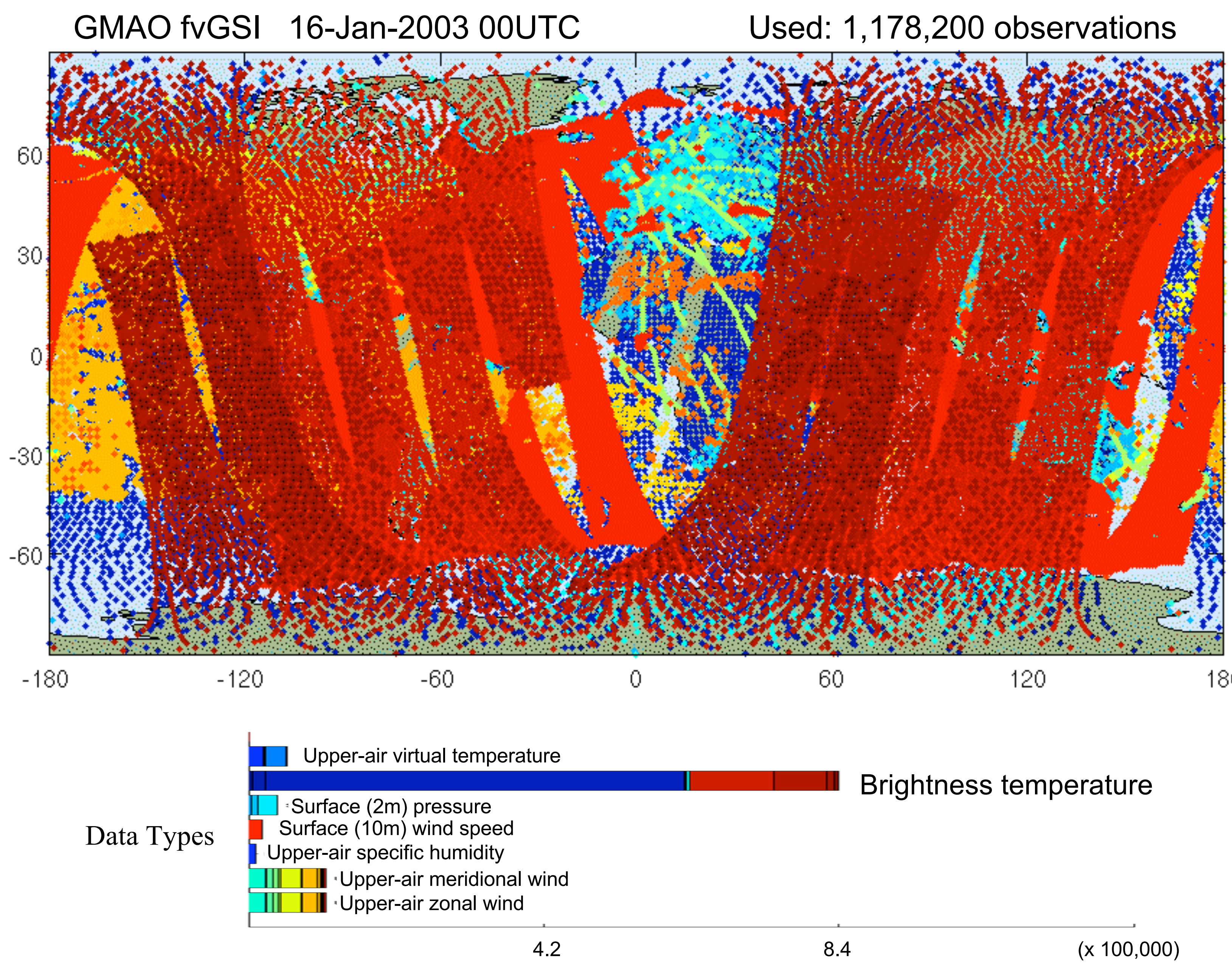
- http://www.esmf.ucar.edu

- Hill, C., C. DeLuca, V. Balaji, M. Suarez, and A. da Silva, 2004: Architecture of the Earth System Modeling Framework. *Computing in Science and Engineering,* **6**, 18-28.

- Collins, N., G. Theurich, C. DeLuca, M. Suarez, A. Trayanov, V. Balaji, P. Li, W. Yang, C. Hill, and A. da Silva, 2005: Design and implementation of components in the Earth System Modeling Framework. *Int. J. High Perf. Comput. Appl*., **19**, 341-350, DOI: 10.1177/1094342005056120.

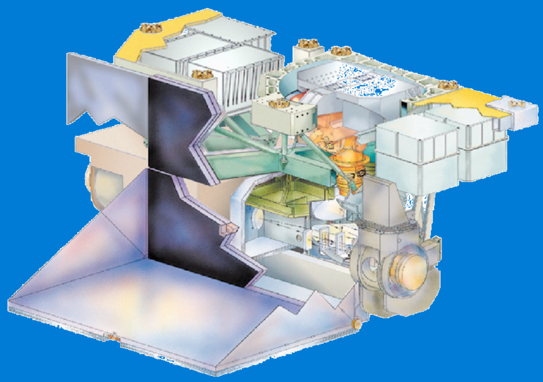

ADAS
Background
error characteristics
Input observations and
error characteristics
Gridpoint Statistical
Interpolation (GSI) Scheme
Observation Operators
3D VAR
Conjugate Gradient Solver
Observation Quality Control
CRTM

The observing system…today



EOS/Aqua: AIRS and MODIS - launched May 2002

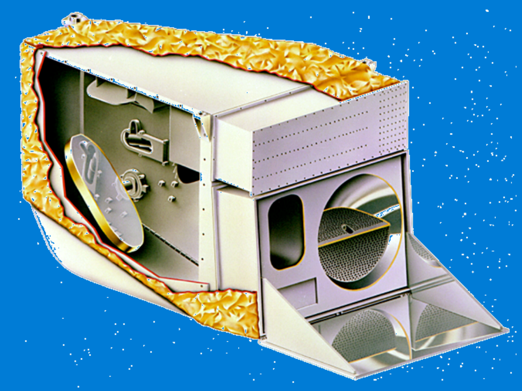
AIRS High Spectral



Atmospheric InfraRed Sounder

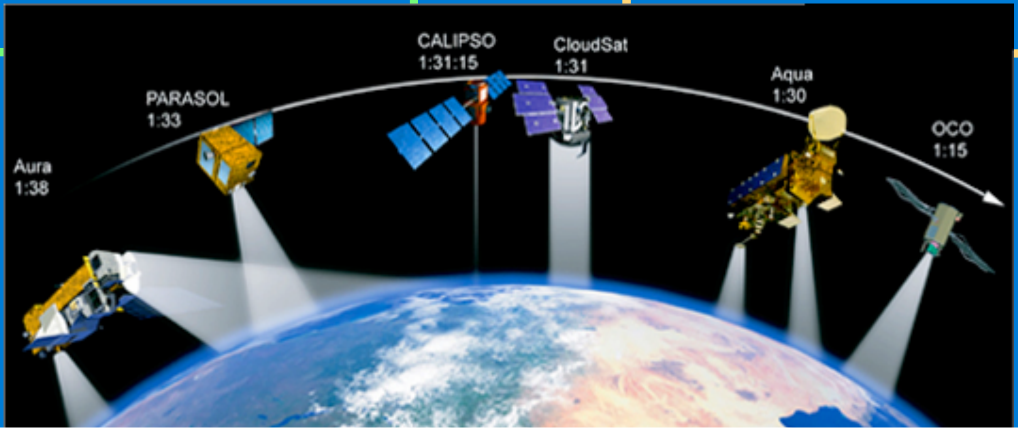
- 13.5 km IR IFOV
- 3.7-15.4 μm IR
- 2378 IR Channels

MODIS High Spatial



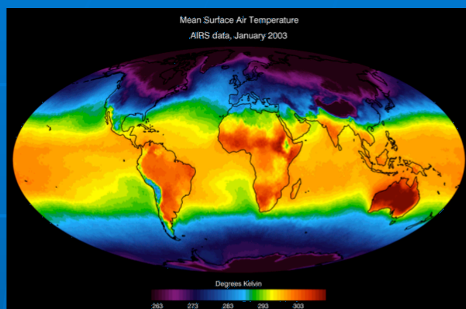
MODerate resolution Imaging Spectroradiometer

-1 km IR IFOV
 0.25-0.5 km VNIR/SW
- 0.4-14.2 μm IR
- 20 RSB, 16 IR Channels

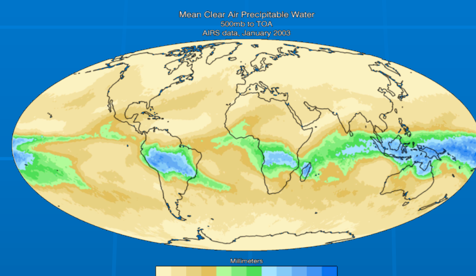


AIRS Products Support Climate Studies

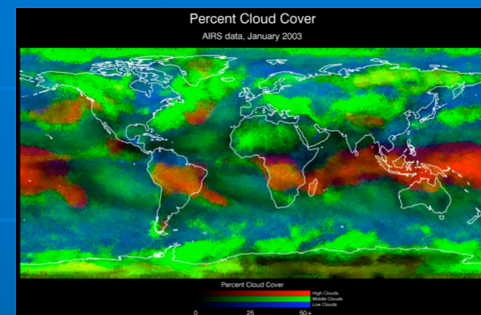
Atmospheric Temperature



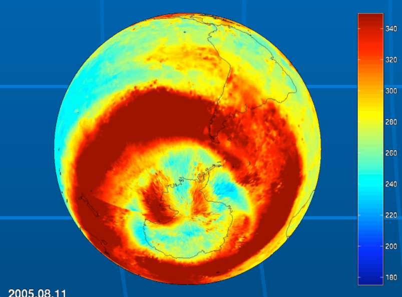
Atmospheric Water Vapor



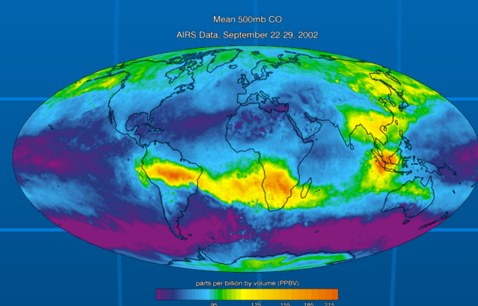
Cloud Properties



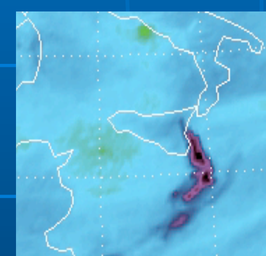
Ozone



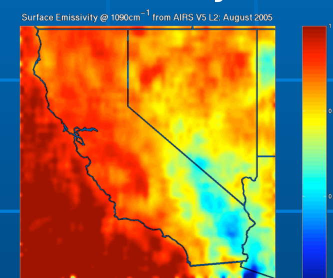
CO



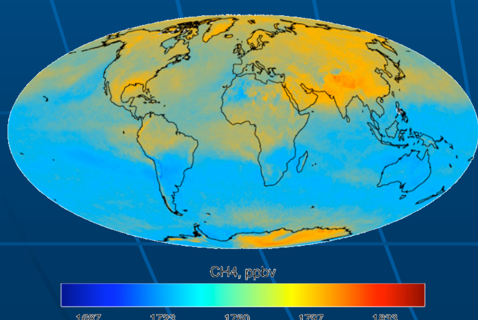
SO2



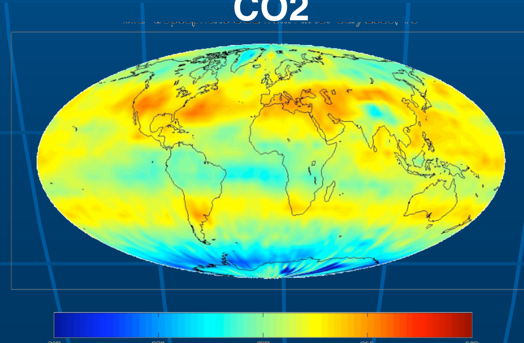
Emissivity



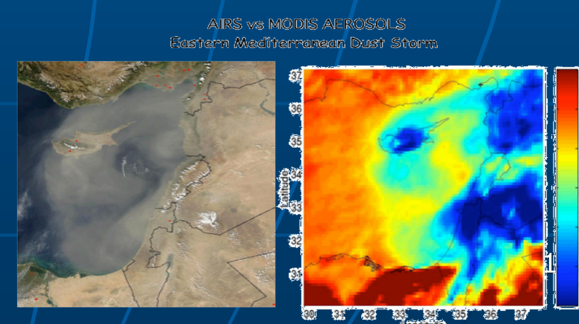
Methane



CO2



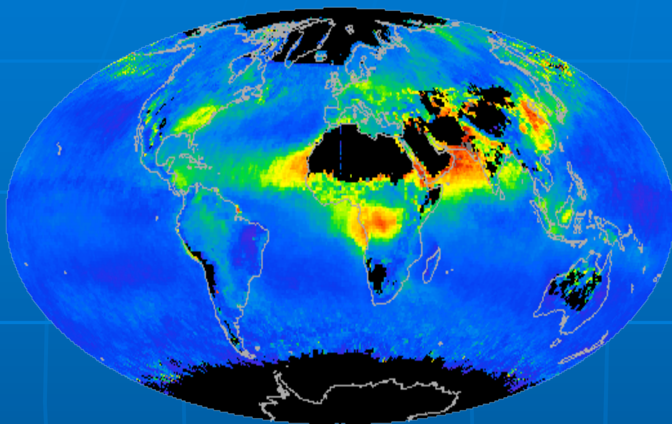
Dust



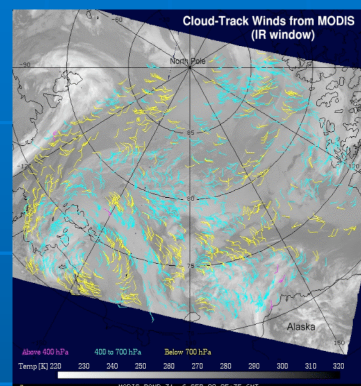
M. Chachine, T. Pagano, C. Parkinson

Example MODIS Products

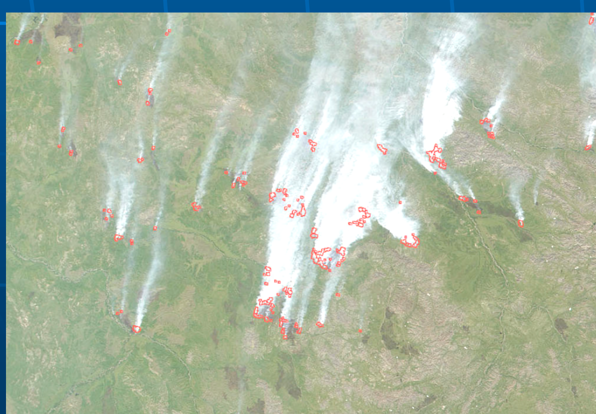
Aerosols



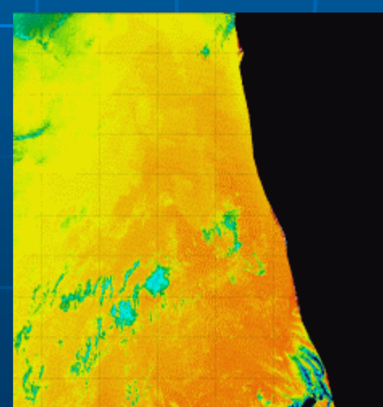
Polar Winds



Fires

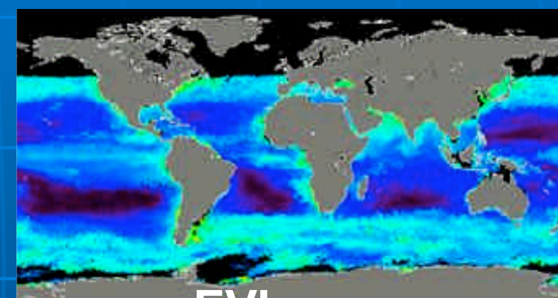


SST



Optional

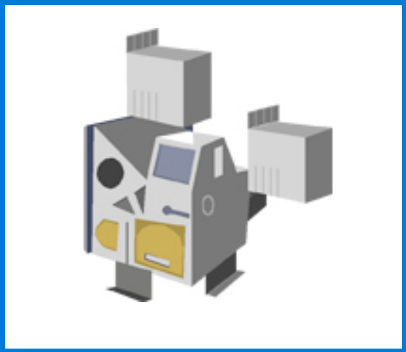
Ocean Chlorophyll



EVI

EOS/Aura: MLS, OMI - launched July 2004

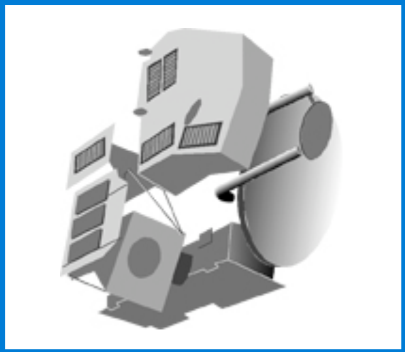
OMI



Ozone Monitoring Instrument

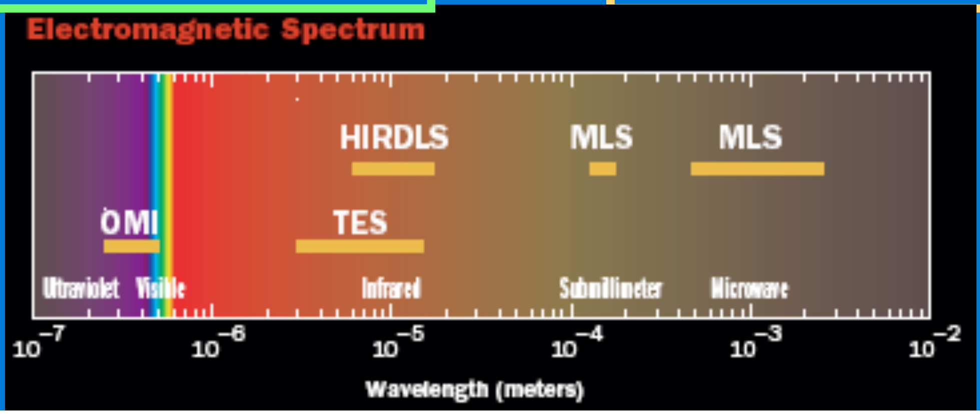
- 3 km, binned to 13 x 24 km IFOV
- 350-500 nm visible
- UV-1, 270 to 314 nm, UV-2 306 to 380 nm
-Total Ozone
- Distinguishes aerosol types (smoke, dust, sulphates)
- The Netherlands and Finland

MLS



Microwave Limb Sounder

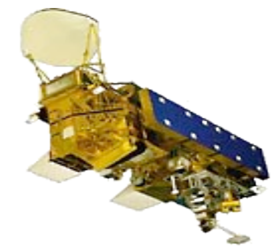
-1.5 km vert × 3km cross-trk × 300 km along-trk MW IFOV
- sub-mm to mm wavelengths
- Stratospheric temperature and upper tropospheric water vapor & ice & constituents



AIRS assimilation

Emily Liu

Assimilation of AIRS in GEOS-5



Configurations

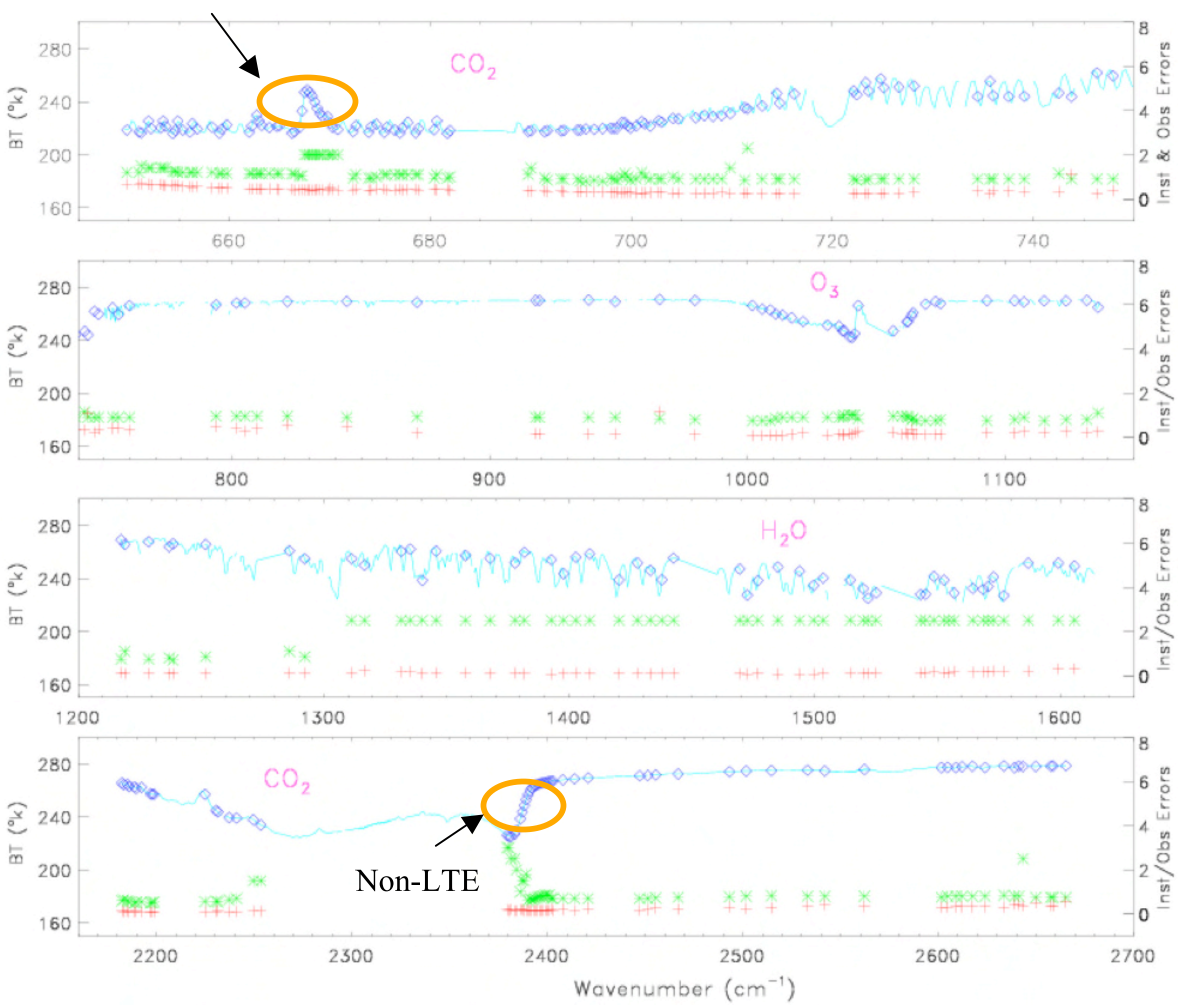
- GEOS-5 Model with IAU
- Other satellite radiance data used within GEOS-5 includes SSMI, MSU, HIRS-2, HIRS-3, AMSU-A, and AMSU-B, and MHS

Two Impact Experiments

- **Trial #1**
  - GEOS-5 Model resolution 1/2° x 2/3° x 72 Levels
  - Period – 2006 January and February
  - Control - baseline no AIRS
  - Focus - control with AIRS
    - Full spatial resolution AIRS data set
    - 251 AIRS channels
- **Trial #2**
  - GEOS-5 resolution **-** 1° x 1.25° x 72 Levels
  - Period - 2003 January
  - Control – baseline with AIRS
    - Thinned AIRS data set
    - 152 AIRS channels
  - Focus – control with AIRS moisture channel turned off
    - 108 AIRS channels

Channel Errors and Selection

High peaking channels
(large model bias)

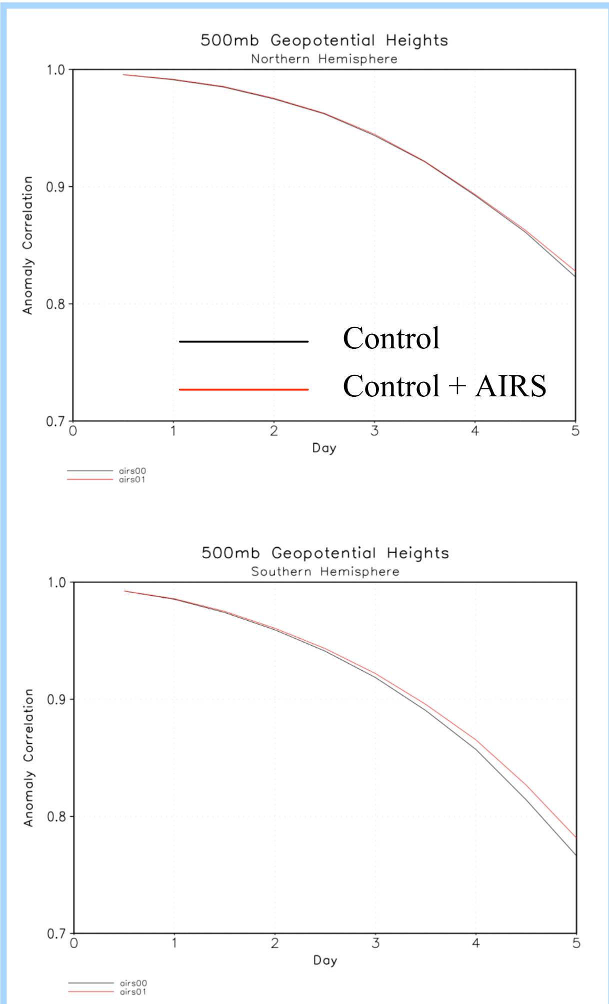


◇ 281 channels + instrument errors * observation errors

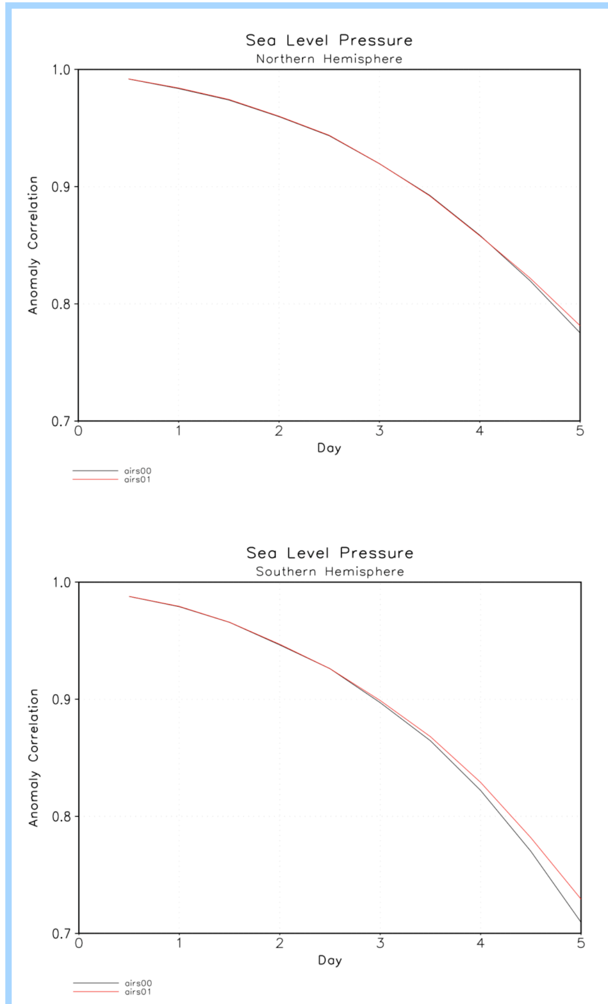
- 251 out of 281 channels were used in the assimilation
  - channel 73-86 removed due to channels peaking in Mesosphere (large background biases)
  - channel 1937-2109 removed due to non-LTE effect
  - Channel 2357 removed due to large noise
- Shortwave channels:
  - wavenumber > 2000 cm^{-1} down weighted
  - Wavenumber > 2400 cm^{-1} used only at night
- NCEP observation errors used
  - Larger error assignment for water vapor channels

The Impact of AIRS --- Trial #1

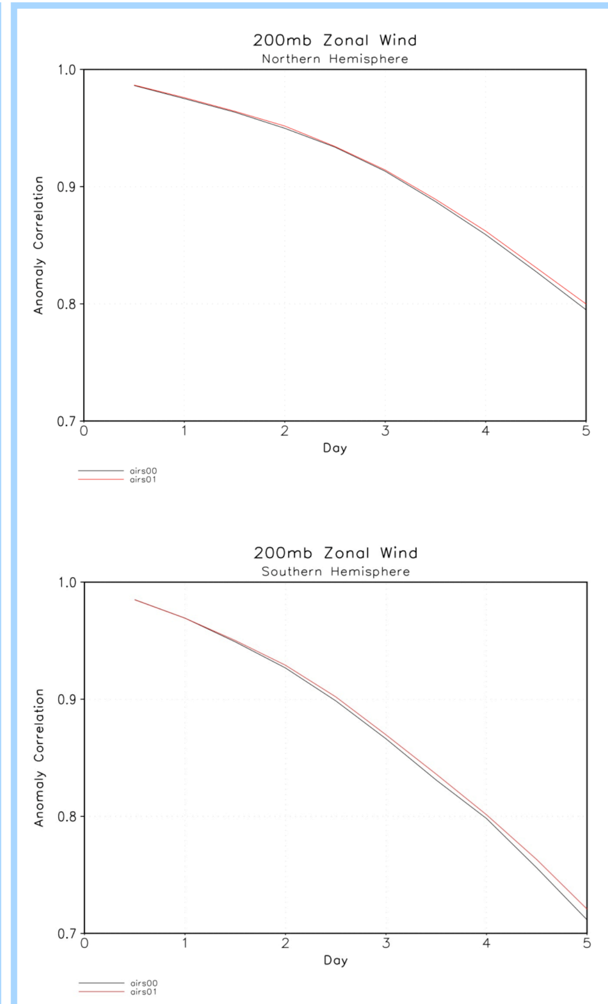
500mb Geopotential Height



Sea Level Pressure



200mb Zonal Wind

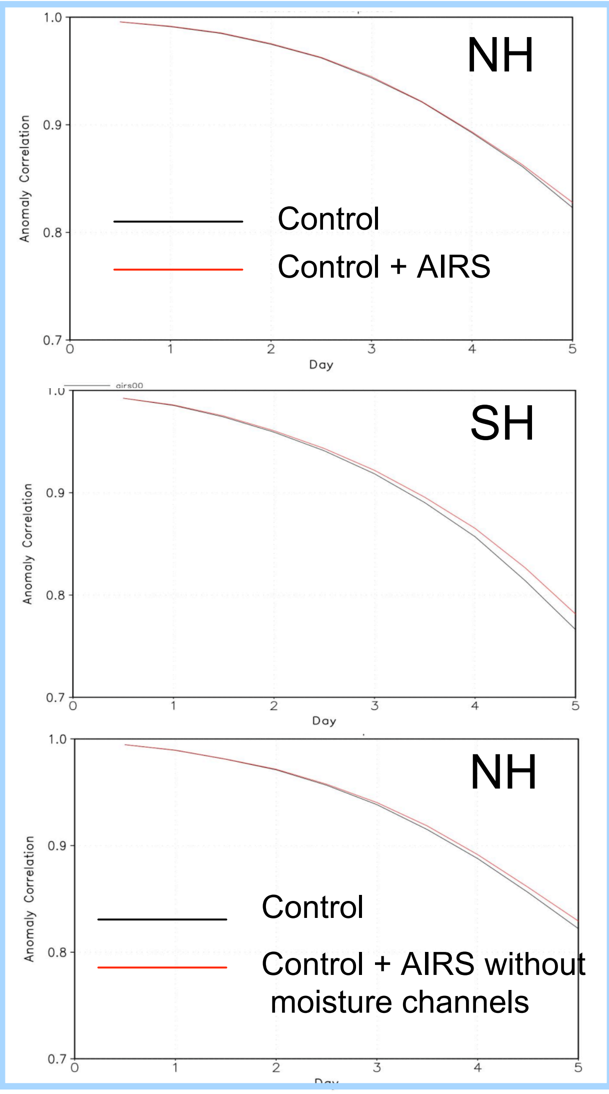


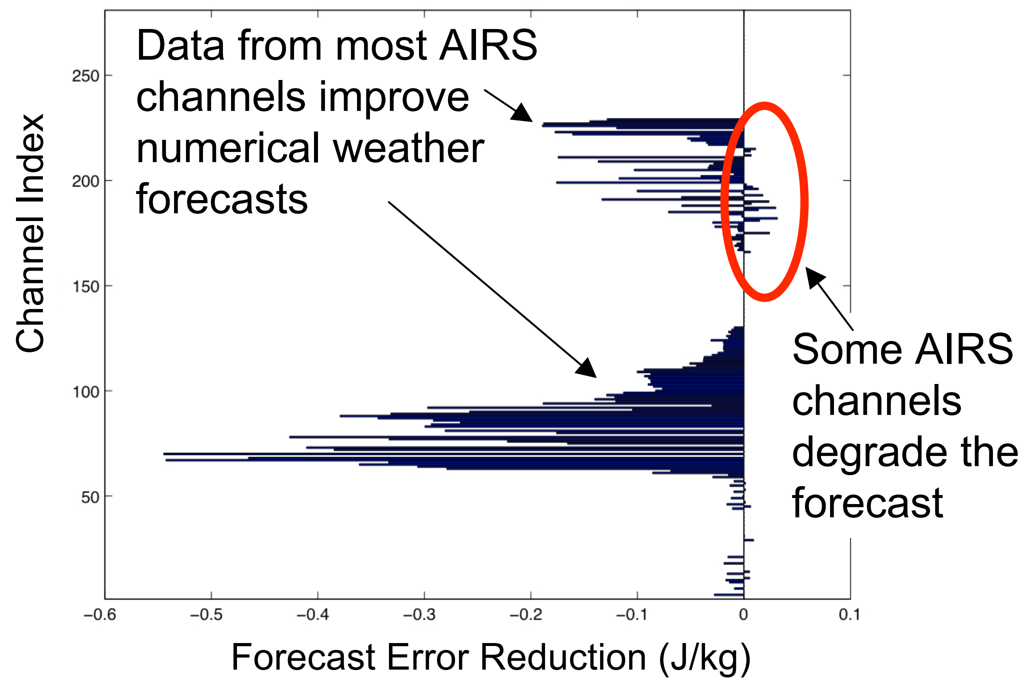
- Forecast skills were calculated based on 59 cases
- Slightly positive impact in North Hemisphere; clear positive impact in South Hemisphere

GEOS-5 used to Evaluate Impact of AIRS in NWP

Emily Liu, Ron Gelaro, Yanqiu Zhu

Forecast Skill vs. Time





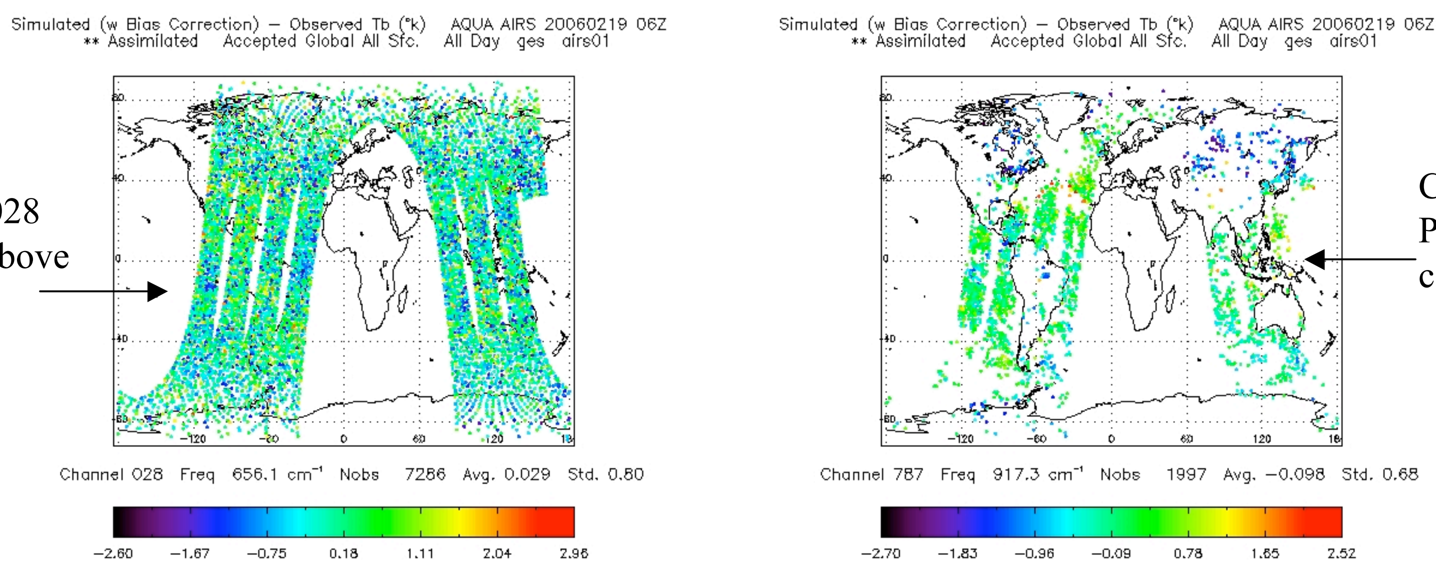
AIRS brings slightly positive impact on forecast skill in Northern Hemisphere; clear positive impact in Southern Hemisphere. But forecast skills are increased when moisture channels from AIRS are not included

Next: Cloud-Cleared AIRS Radiances

- **Background**
  - The presence of clouds has drastically limited the ability to use AIRS data so far. Currently, only clear AIRS channels are used in most of the data assimilation systems.
  - The direct use of cloudy AIRS data is currently prohibited by the immense computational burden in accurate infrared cloudy radiative transfer calculations
  - Cloud-cleared AIRS radiances can provide sounding data beneath the clouds and may potentially beneficial in numerical weather forecasting especially in the troposphere.

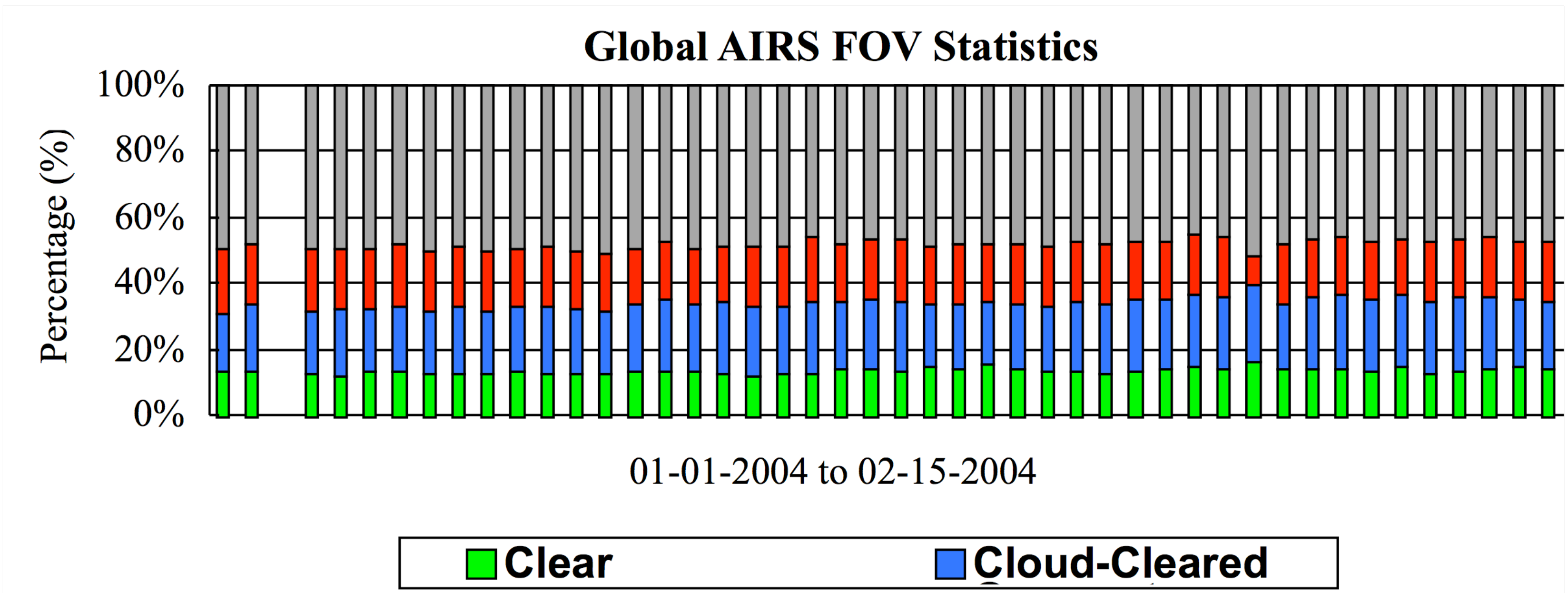
Assimilated Data Coverage

Channel 028
Peaking above
clouds



Channel 787
Peaking below
clouds

- **AIRS/MODIS Synergistic Cloud-Clearing Approach**
  - Cloud-clearing is a procedure that removes cloud radiative effects through comparison of partly cloudy adjacent pixels
  - Optimal cloud clearing procedures to retrieve clear column radiances for all AIRS Channels can be obtained by combining collocated MODIS IR clear radiance observations and the AIRS cloudy radiance measurements
  - The collocated MODIS pixels along with their cloud mask, cloud phase mask, and cloud height information can help to determine the cloud properties within the AIRS footprints
  - No background information is needed
  - Results indicate that approximately 13% of the AIRS footprints are clear, and 21% of the AIRS footprints can be cloud cleared successfully



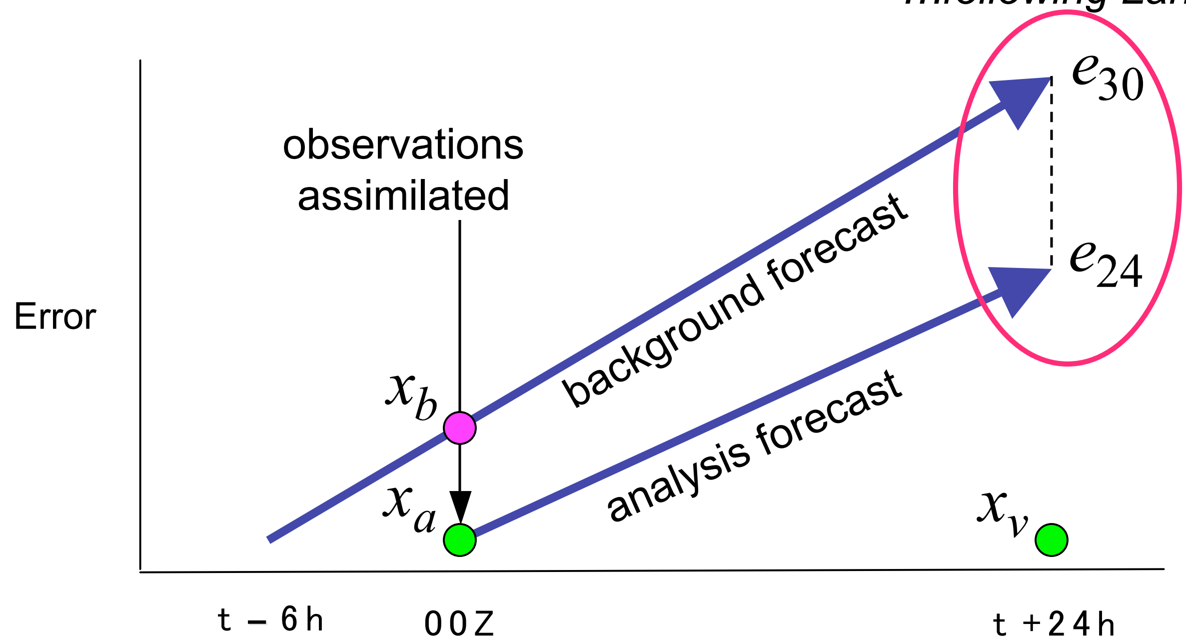
AIRS impacts on forecasts evaluated using adjoint sensitivity tools

Ron Gelaro, Yanqiu Zhu, Emily Liu

Using Adjoints to Assess Observation Impact on Forecast Error

Ron Gelaro and Yanqiu Zhu

…following Langland and Baker 2004



- The difference $e_{24} - e_{30} = \Delta e_{24}^{30}$ is due entirely to the assimilation of observations at 00Z ⇒ *measures the impact of the observations*
- $\Delta e_{24}^{30} < 0$ indicates that the error of the forecast started from x_a is less than that started from x_b ⇒ *the observations are beneficial*
- Δe_{24}^{30} can be estimated as a sum of *contributions from individual observations* using information from the model and analysis adjoints together

Data Assimilation-Forecast System

Atmospheric forecast model:

$$\mathbf{x}^f = \mathbf{m}(\mathbf{x}_0)$$

Atmospheric analysis (best estimate of $\mathbf{x}_0$) :

$$x_a = x_b + K[y - h(x_b)]$$

where: $\boldsymbol{x}_\mathrm{a} - \boldsymbol{x}_\mathrm{b} = \boldsymbol{\delta x}_0$ (correction vector)

$\boldsymbol{y} - \boldsymbol{h}(\boldsymbol{x}_\mathrm{b}) = \boldsymbol{\delta y}$ (innovation vector ~10^6)

Note that for any vector $\mathbf{g}$ in state space there is a corresponding vector $\tilde{\mathbf{g}}$ in observation space such that:

$$\tilde{\mathbf{g}} = \mathbf{K}^\mathrm{T}\mathbf{g}$$

Estimating Observation Impact

Forecast error measure (global dry energy):

$$e = (\mathbf{x}_0^f - \mathbf{x}_\mathrm{v})^\mathrm{T} \mathbf{C} (\mathbf{x}_0^f - \mathbf{x}_\mathrm{v})$$

Change in e due to change in $\mathbf{x}_0$:

$$\delta e = \delta \mathbf{x}_0 \left(\frac{\partial e}{\partial \mathbf{x}_0} + \frac{1}{2} \frac{\partial^2 e}{\partial \mathbf{x}_0^2} \delta \mathbf{x}_0 + \frac{1}{6} \frac{\partial^3 e}{\partial \mathbf{x}_0^3} \delta \mathbf{x}_0^2 + \ldots \right) = (\delta \mathbf{x}_0)^\mathrm{T} \mathbf{g}$$

Transformation to observation-space:

$$(\delta \mathbf{x}_0)^\mathrm{T} \mathbf{g} = (\delta \mathbf{y})^\mathrm{T} \tilde{\mathbf{g}}$$

3rd order approximation of δe in observation space:

$$\boldsymbol{\delta} e \approx (\boldsymbol{\delta y})^\mathrm{T} \boldsymbol{K}^\mathrm{T} [\boldsymbol{M}_\mathrm{b}^\mathrm{T} \boldsymbol{C} (\boldsymbol{x}_\mathrm{b}^f - \boldsymbol{x}_\mathrm{v}) + \boldsymbol{M}_\mathrm{a}^\mathrm{T} \boldsymbol{C} (\boldsymbol{x}_\mathrm{a}^f - \boldsymbol{x}_\mathrm{v})] = (\boldsymbol{\delta y})^\mathrm{T} \tilde{\boldsymbol{g}}_3$$

assilimation adjoint

model adjoint

…summed observation impact

GEOS-5 Observation Impact Experiments

Analysis System

- 3DVAR Gridpoint Statistical Interpolation (GSI, Wu et al. 2002)
- 0.5^o resolution, 72 levels
- Conventional observations + radiances, AIRS
- 2 outer loops x 100 iterations
- **Adjoint:** Exact line-by-line (Zhu and Gelaro 2007)

Forecast Model

- GEOS-5: FV-core + full physics, ESMF structure
- 1.25^o resolution, 72 levels
- **Adjoint:** FV-core + simple dry physics (Giering et al. 2006)

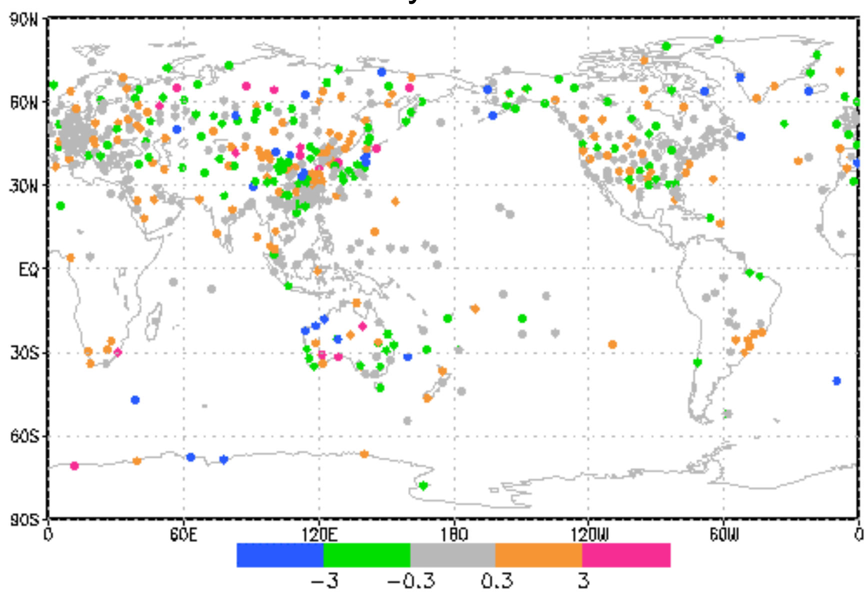
Experimentation

- 6h data assimilation cycle, 15 June – 31 July 2005
- **24h forecasts** from 00z to assess **observation impact**, July 2005

Observation Impact on GEOS-5 24h Forecast Error

Impact of 500mb RAOB Temps

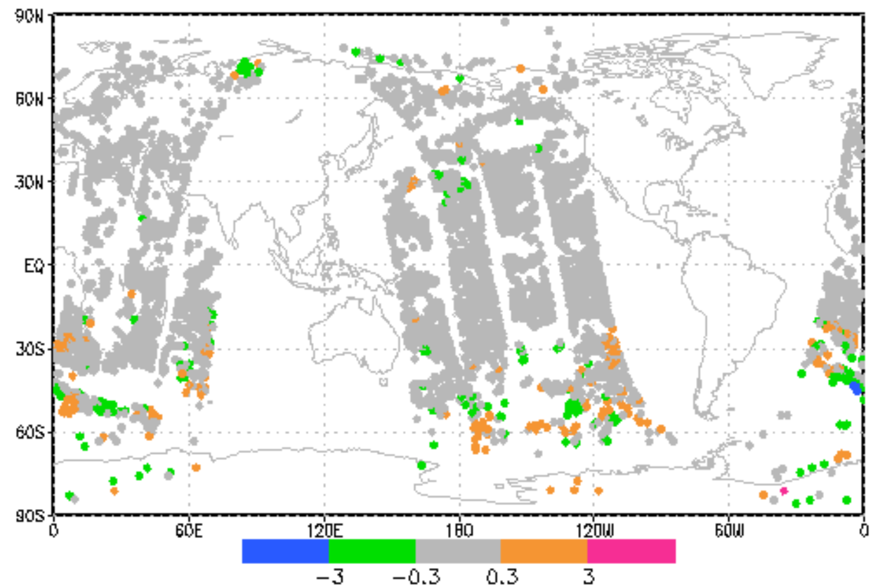
10 July 2005 00z



Error Reduction Error Increase

Impact of AIRS Ch.221 Radiances

10 July 2005 00z



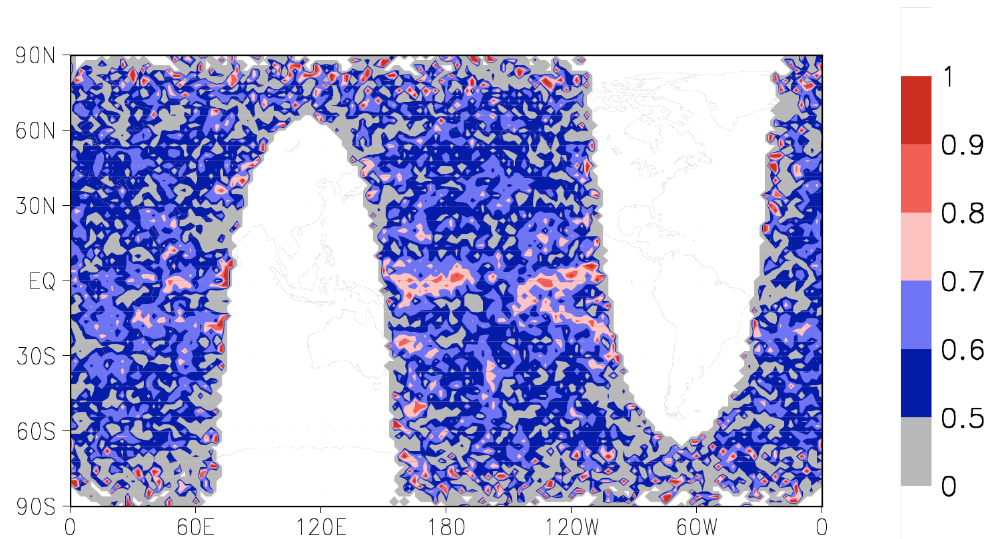
Error Reduction Error Increase

- Observations that reduced the 24h forecast error: $\delta e < 0$
- Observations that increased the 24h forecast error: $\delta e > 0$
- Observations that had small impact on 24h forecast error

…more details of observation impact

GEOS-5 July 2005 00z

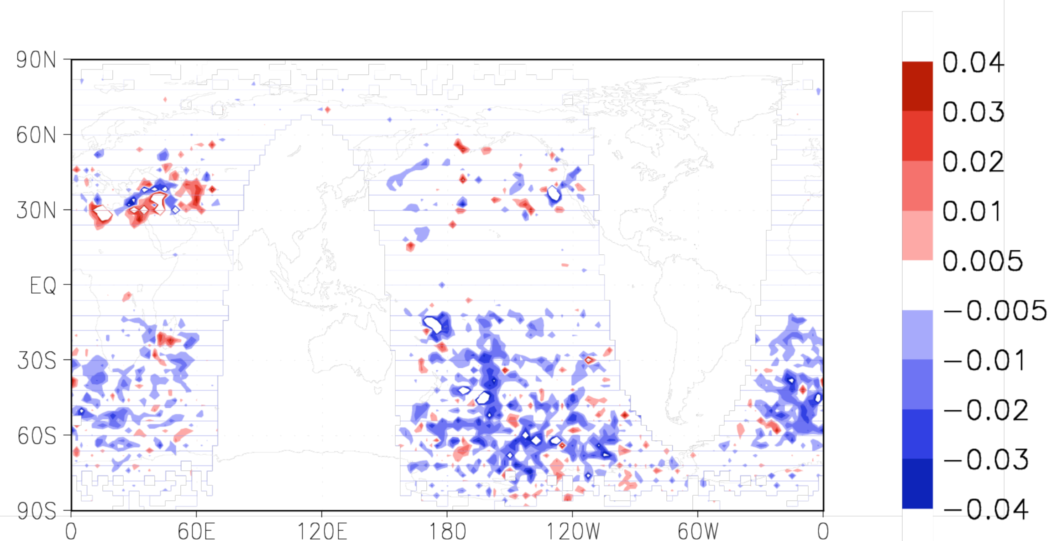
Fraction of **AIRS** observations that improve forecast



~55% of sat obs provide benefit on average

degrade

Impact of **AIRS** observations on forecast



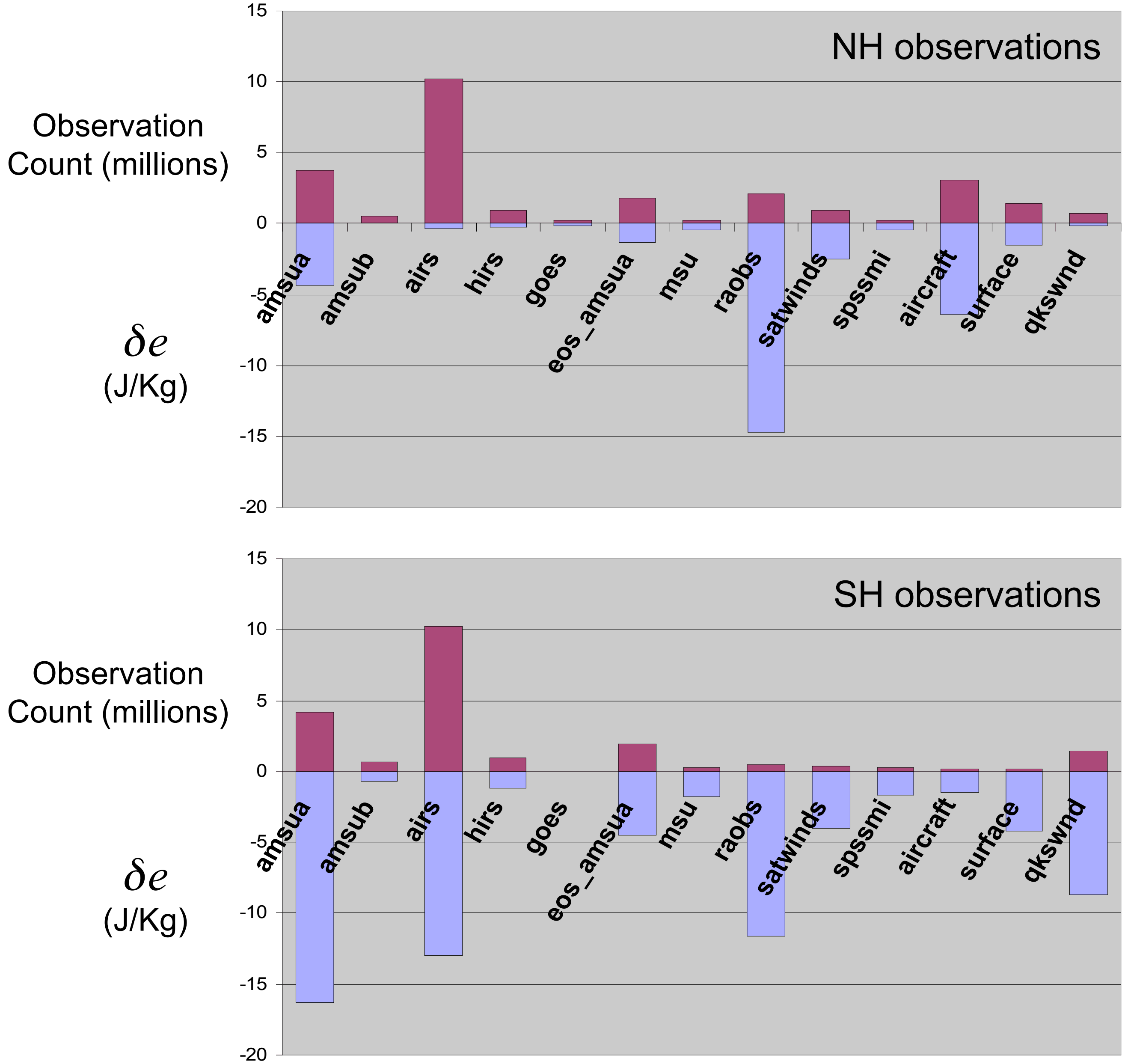
degrade

J/kg

improve

Impacts of various observing systems Totals

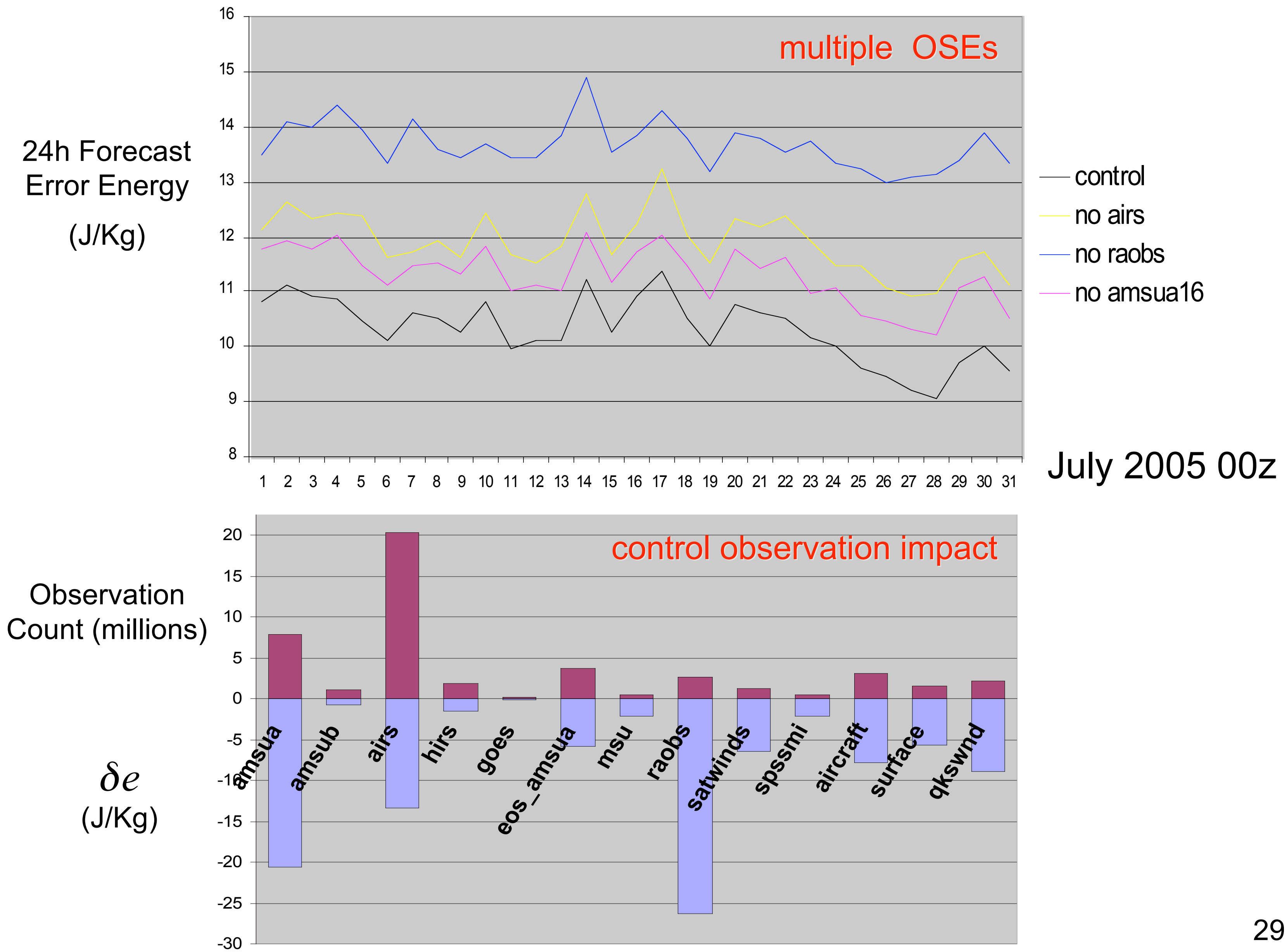
GEOS-5 July 2005



…all observing systems provide total monthly benefit

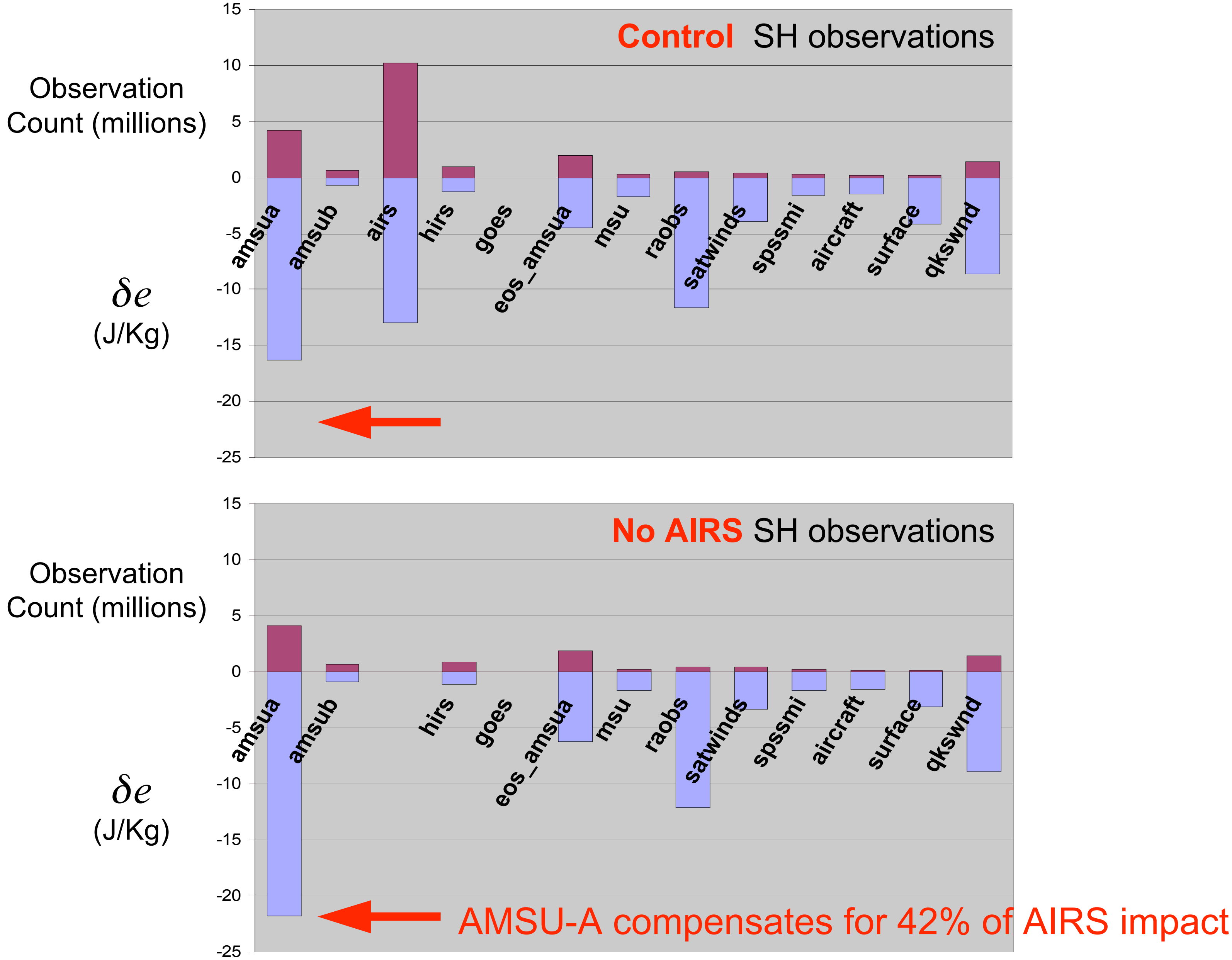
GEOS-5 Observation Impact: Comparison with OSEs

Ron Gelaro and Yanqiu Zhu



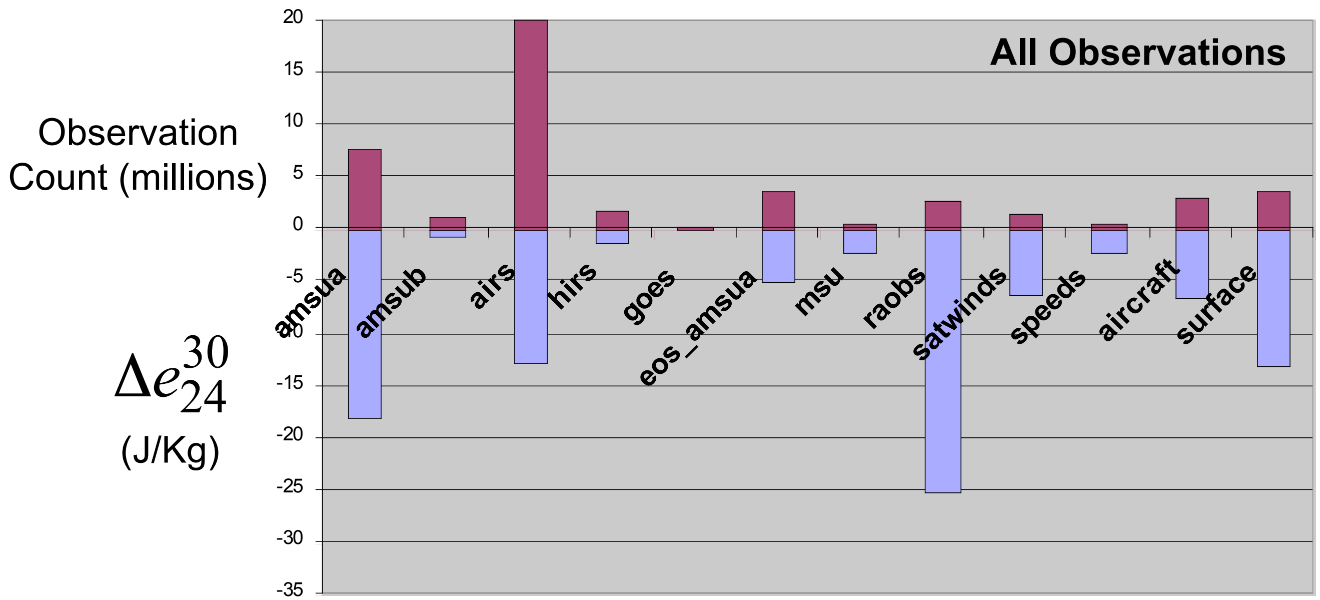
Adjoint system as complement to OSEs

GEOS-5 July 2005

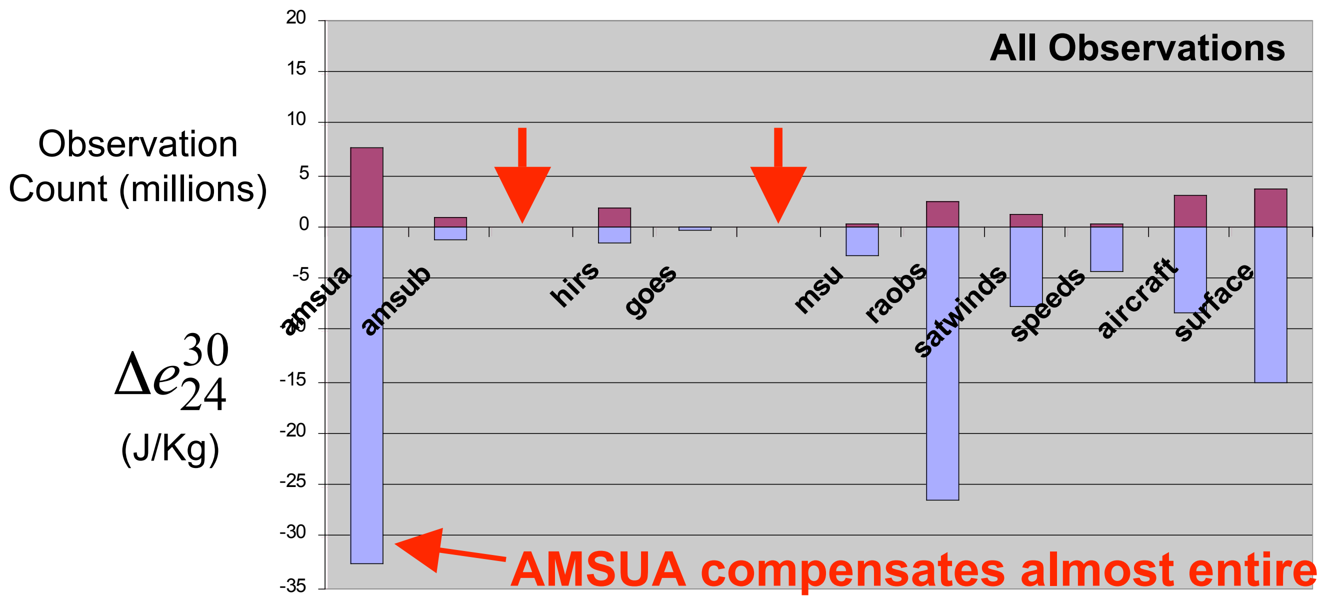


GEOS5 Observation Impact: July 2005 00z

Totals for AQUA data denial experiments



Control All Data



Without AQUA AIRS+AMSUA

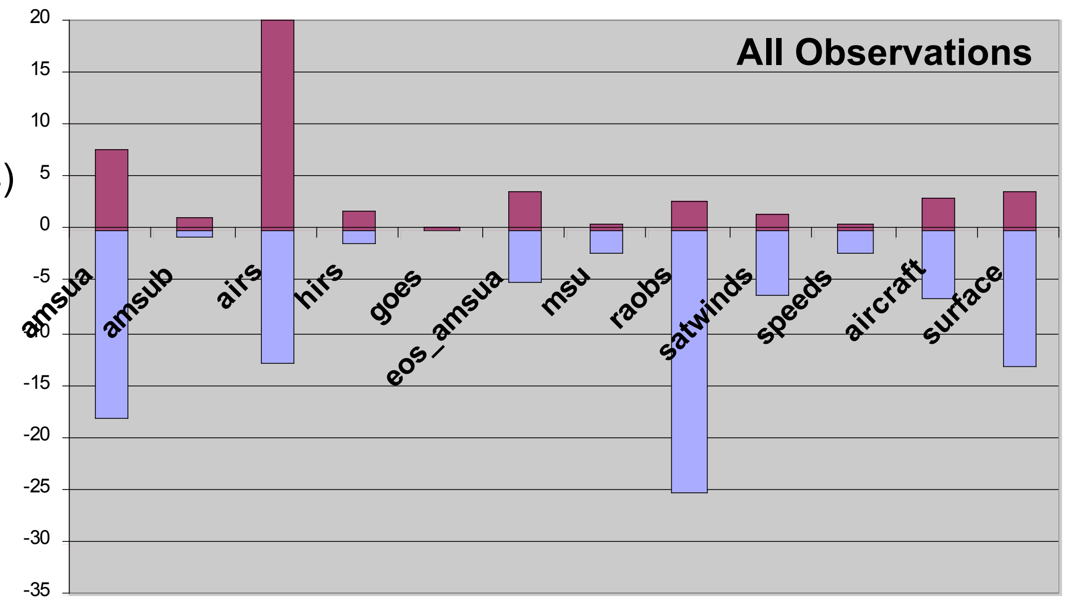
AMSUA compensates almost entirely for AQUA data

GEOS5 Observation Impact: July 2005 00z

Totals for AMSUA data denial experiments

Observation Count (millions)

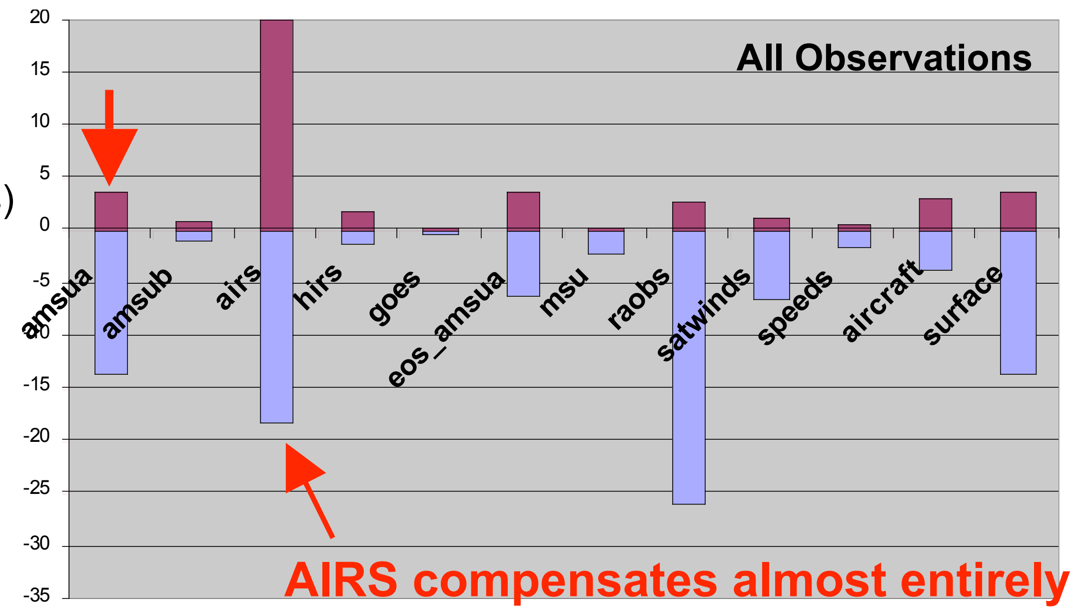
Δe_{24}^{30} (J/Kg)



Control All Data

Observation Count (millions)

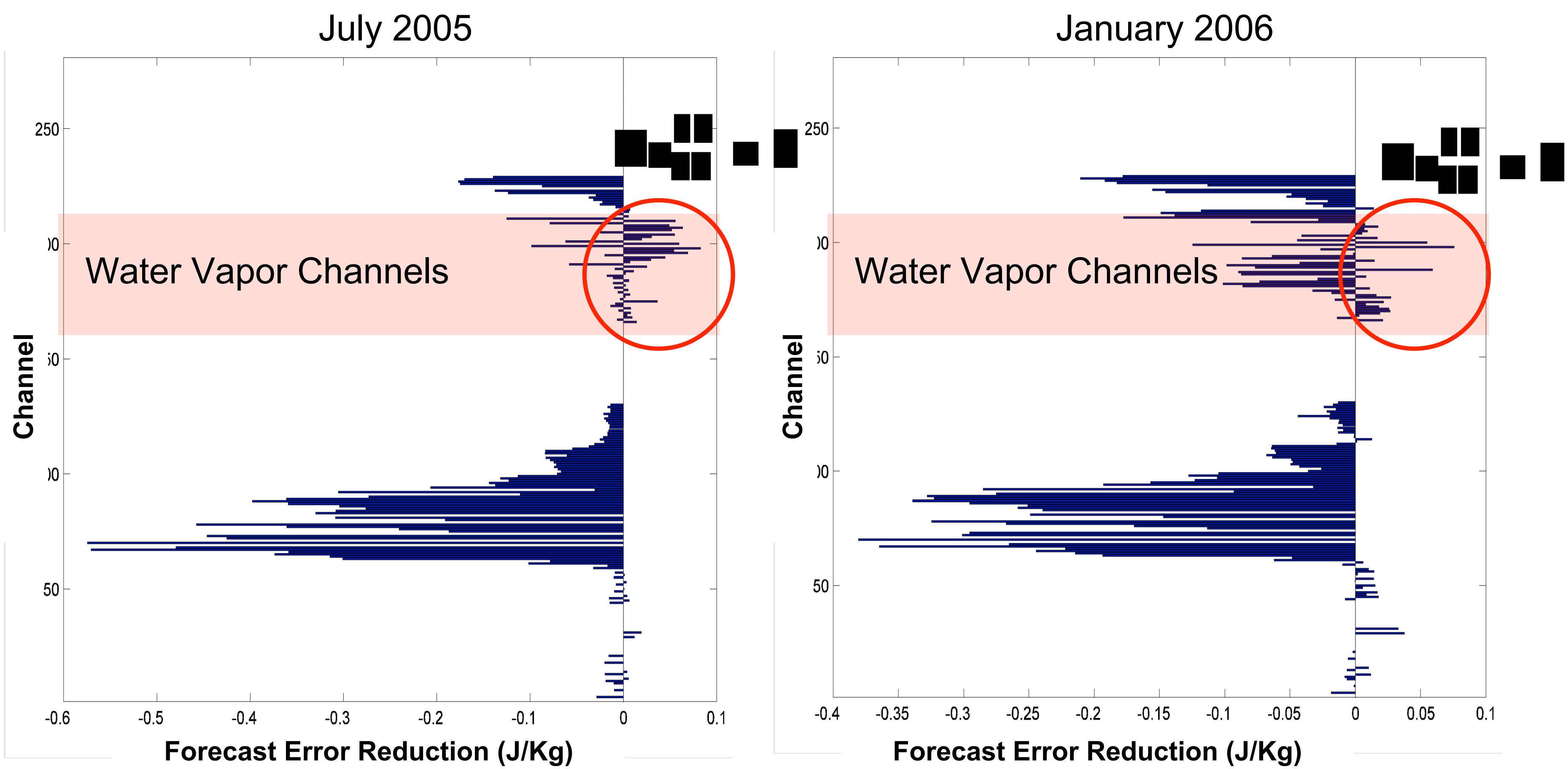
Δe_{24}^{30} (J/Kg)



Without NOAA16 AMSU-A

AIRS compensates almost entirely for AMSUA data

GEOS5 Observation Impact: Totals for AIRS Channels



A significant fraction of AIRS water vapor channels currently degrade the 24-h forecast in GEOS-5…investigation under way.

Conclusions

• Data assimilation system adjoint provides an accurate and efficient tool for estimating observation impact on analyses and forecasts

✓ computed with respect to all observations simultaneously

✓ permits arbitrary aggregation of results by data type, channel, location, etc.

• Applications to data quality assessment and selection, system performance, specification of future observing requirements,…

• Complement and extend, but not necessarily replace, traditional OSEs as tools for assessing observation impact

• Comparisons of impacts in different forecast systems should help clarify deficiencies in data quality vs. assimilation methodology, and provide valuable feedback to data producers.

Some references:

• Langland, R.H. and N. Baker, 2004: Estimation of observation impact using the NRL atmospheric variational data assimilation adjoint system. *Tellus*, **56**, 189-201.

• Errico, R.M., 2007: Interpretations of an adjoint-derived observational impact measure. *Tellus*, **59**, 273-276.

• Zhu Y. and R. Gelaro, 2007: Observation sensitivity calculations using the adjoint of the Gridpoint Statistical Interpolation (GSI) analysis system. *Mon. Wea. Rev.* (in press). (preprint available at http://gmao.gsfc.nasa.gov/research/assimilation/GSIadj_paper.pdf)

Ozone Assimilation

Ivanka Stajner

Ozone in GEOS-5 DAS

Data:

- **SBUV** and **OMI** ozone
- **TOVS** and **AIRS** radiances
- **MLS** retrieved stratospheric ozone profiles

Model:

- Transport in GCM
- Parameterized chemistry (production and loss rates)

GSI-model interface uses Incremental Analysis Update

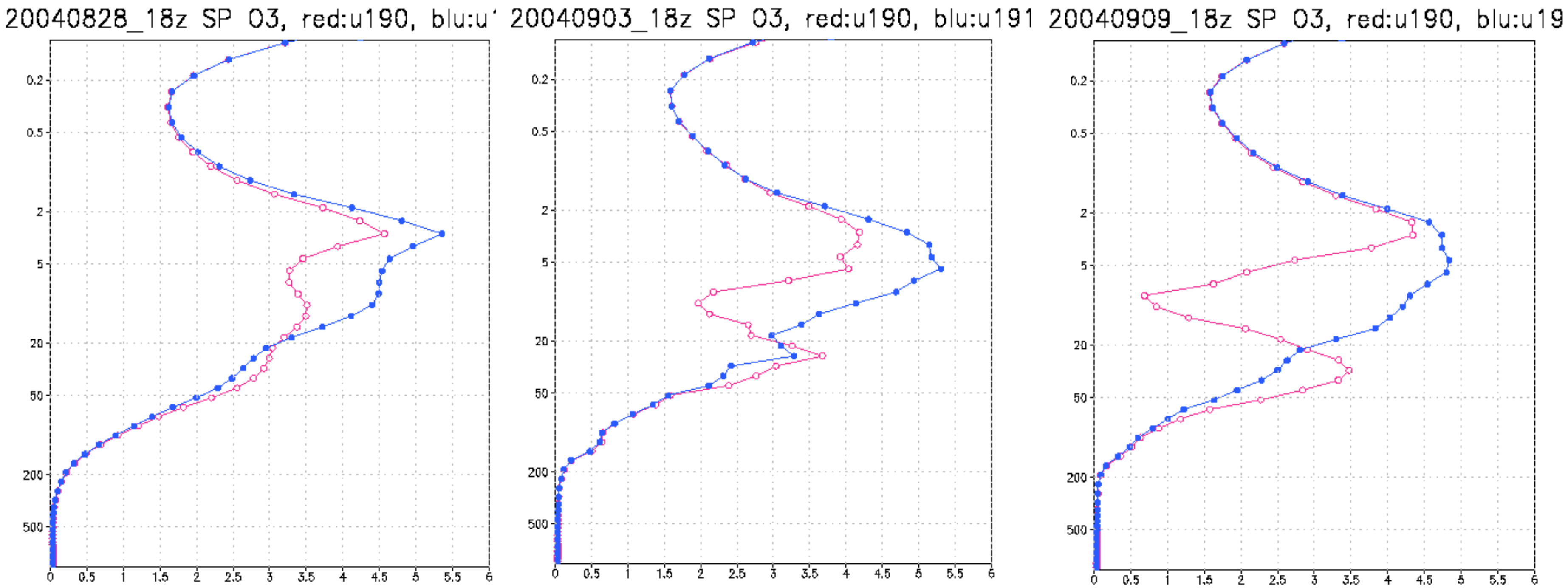
Prognostic ozone used in:

- Radiative heating computations in GCM
- Assimilation of IR radiances

AIRS and polar ozone

- In standard configuration AIRS ozone channels (around 9.6 μm) are not used.
- Other AIRS channels are sensitive to ozone.
- AIRS has an adverse impact on GEOS-5 ozone during polar night
  - No SBUV or OMI data present
  - GSI increments from AIRS systematically reduce ozone
  - Increments arise from AIRS water vapor channels
  - Increments coincide with polar stratospheric clouds
- Problem larger in the Antarctic, but also seen in the Arctic.

Impact of AIRS in polar night



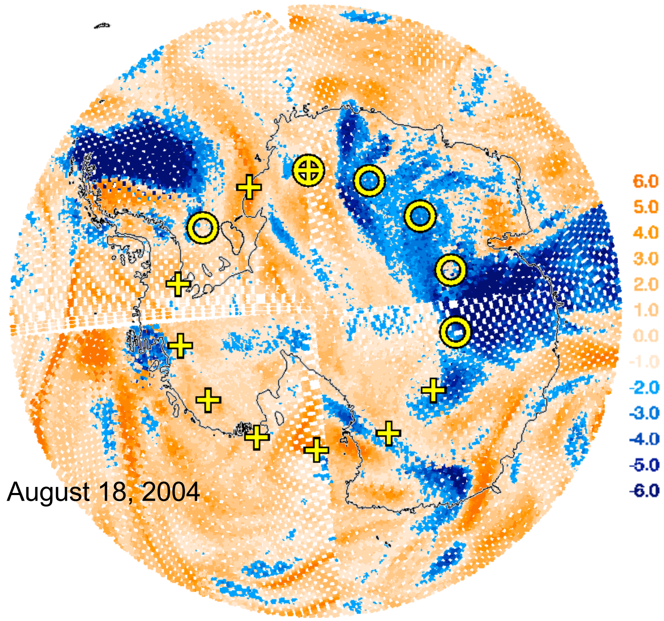
Runs start on August 27, 2004

GEOS-5 crashed in GCM on Sept. 10

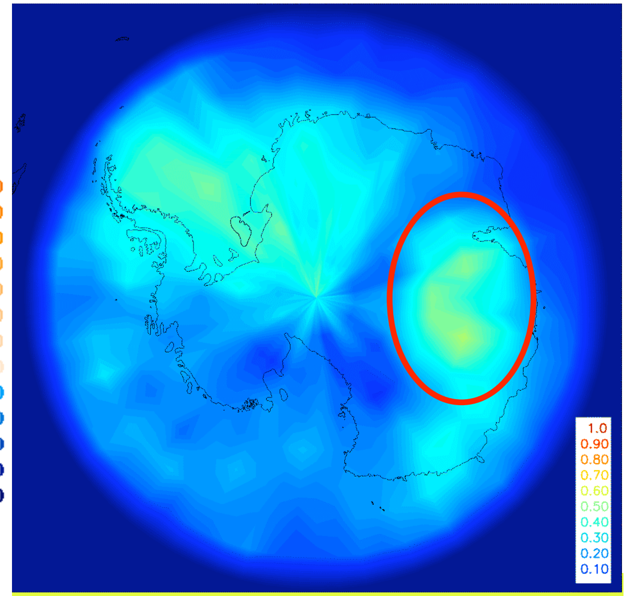
- Ozone profiles at South Pole
- 152 AIRS channels used: not ozone channels 1003-1285
- Red – other AIRS channels impact ozone
- Blue – impact of AIRS on ozone turned off

Ice Polar Stratospheric Clouds (PSCs) Detected from Assimilation of AIRS Data

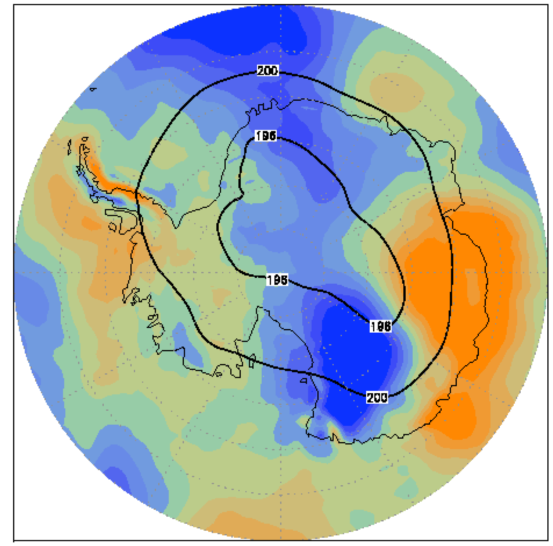
Ivanka Stajner



AIRS observations-minus-**GEOS-5** forecast (O-Fs) for 6.79µm “moisture” channel. The forecast is computed using the CRTM assuming that clouds are not present. O-Fs lower than –2K (blue) typically coincide with locations where POAM III detected ice PSCs (◎).



High frequency of AIRS O-Fs lower than -2K indicates frequent ice PSCs in an unusual region during August 2004.



This is a cold region (temperature contours) with frequent upwelling (orange) during August 2004 at 200 hPa over Antarctica.

I. Stajner, C. Benson, H.-C. Liu, S. Pawson, N. Brubaker, L.-P. Chang, L. P. Riishojgaard and R. Todling (GMAO). *Geophysical Research Letters (in press).*

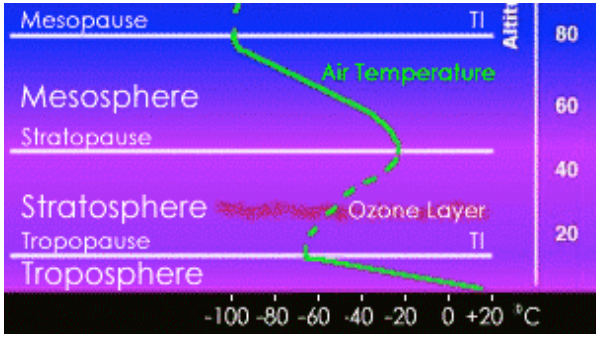
Contact: ivanka@gmao.gsfc.nasa.gov

Ozone: status and plans

- AIRS ozone assimilation in GEOS-5 highlights the complex interactions between the model, data and analysis methodology

- GEOS-5 development
  - Modify quality control for AIRS moisture channels to eliminate PSC-contaminated data
  - Include AIRS ozone channels with appropriate quality control

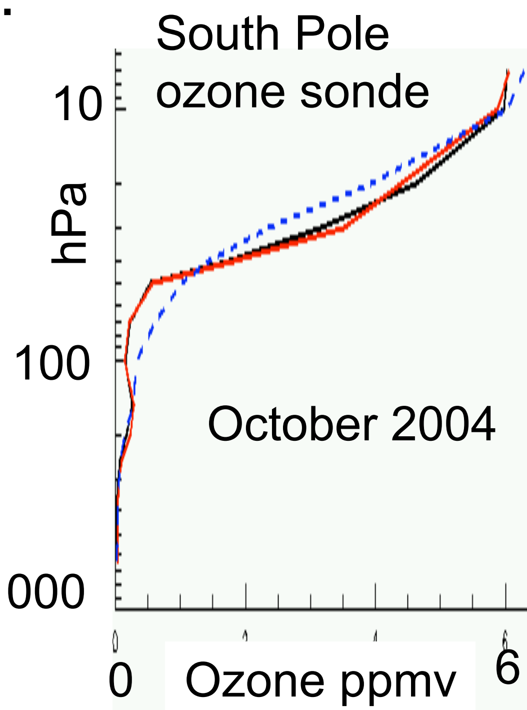
- AIRS moisture channels are being exploited to generate maps of thick PSCs...lead to eventual improvement in detection of PSCs…

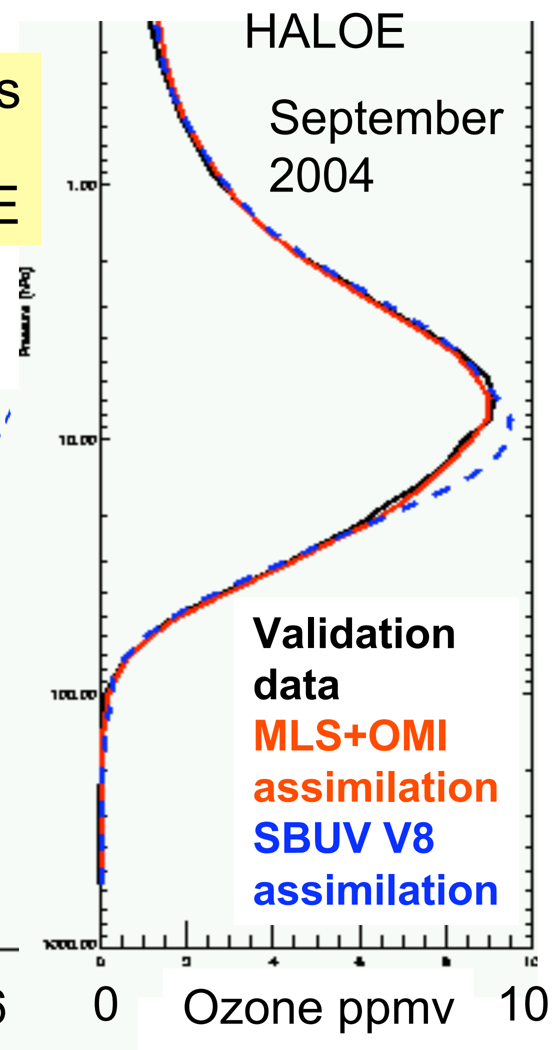


Atmospheric structure and radiative transfer

- Assimilation of MLS+OMI was compared with SBUV V8 assimilation in GEOS-5
- Assimilated ozone used in:
  - assimilation of IR data
  - radiation computations
- A modest impact on the forecast skill at 500 hPa (a couple of hours)
- ~0.5 K impact on the brightness temperatures for channels near 9.6 µm

MLS+OMI improves the agreement with sondes and HALOE



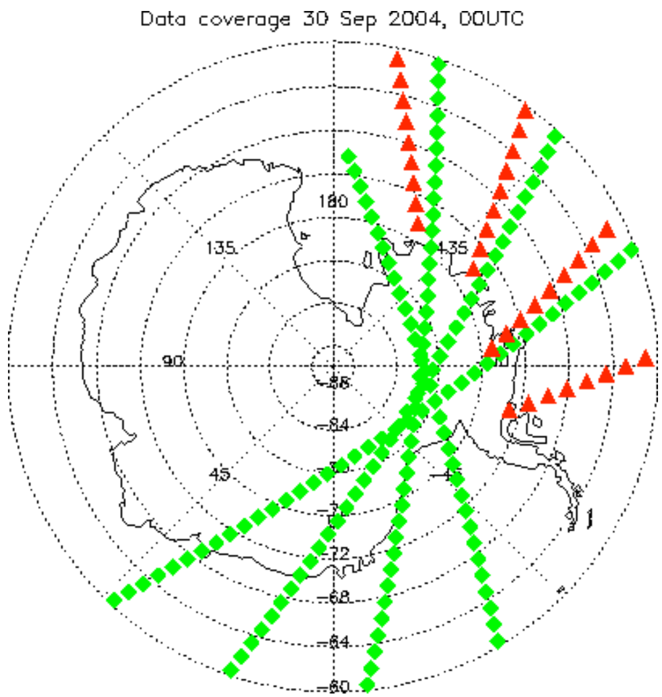


Assimilating AURA/MLS ozone

Meta Sienkiewicz and Ivanka Stajner

SBUV daytime only – no data near South Pole due to high solar zenith angle

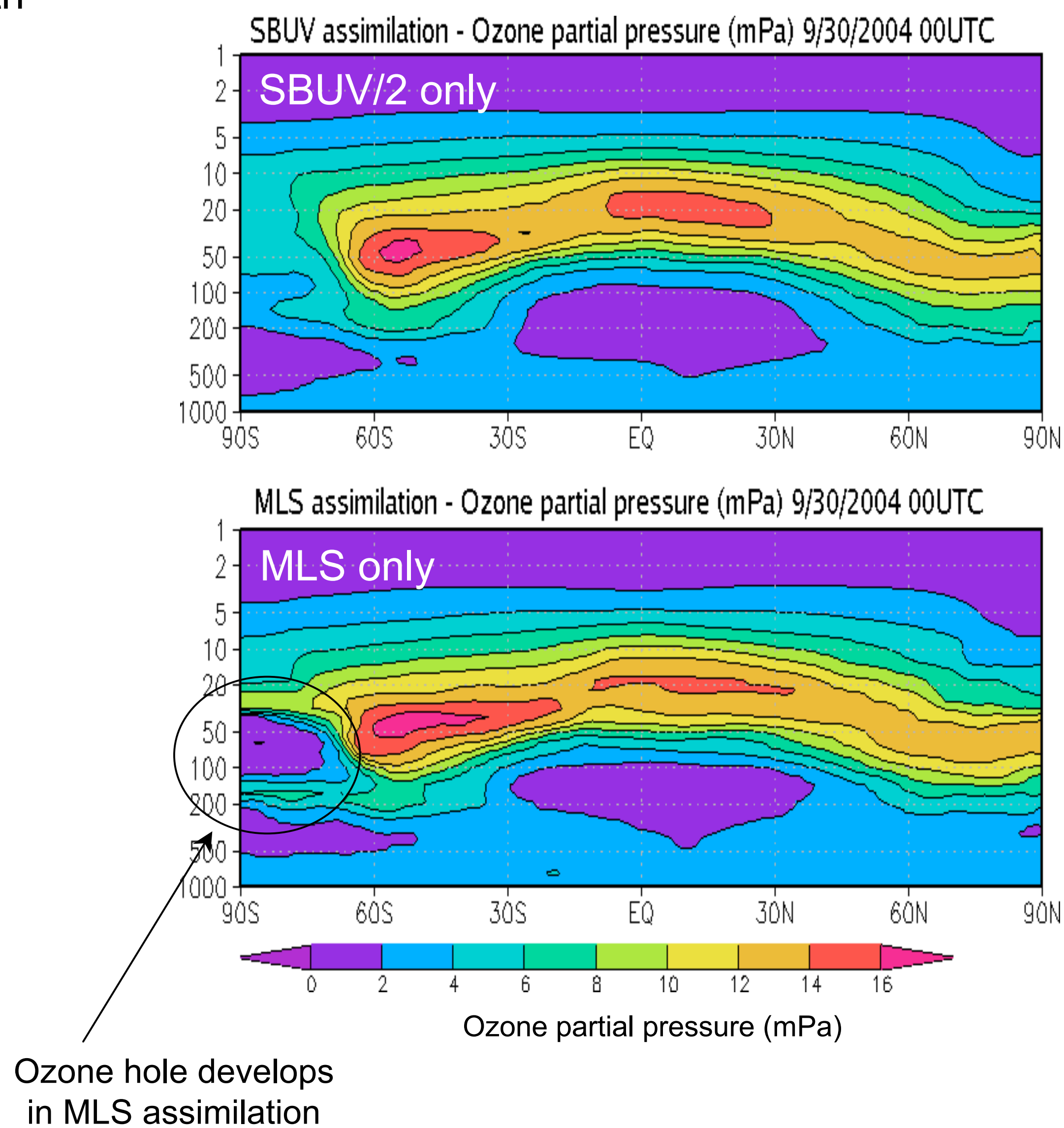
MLS orbital limit ±82º



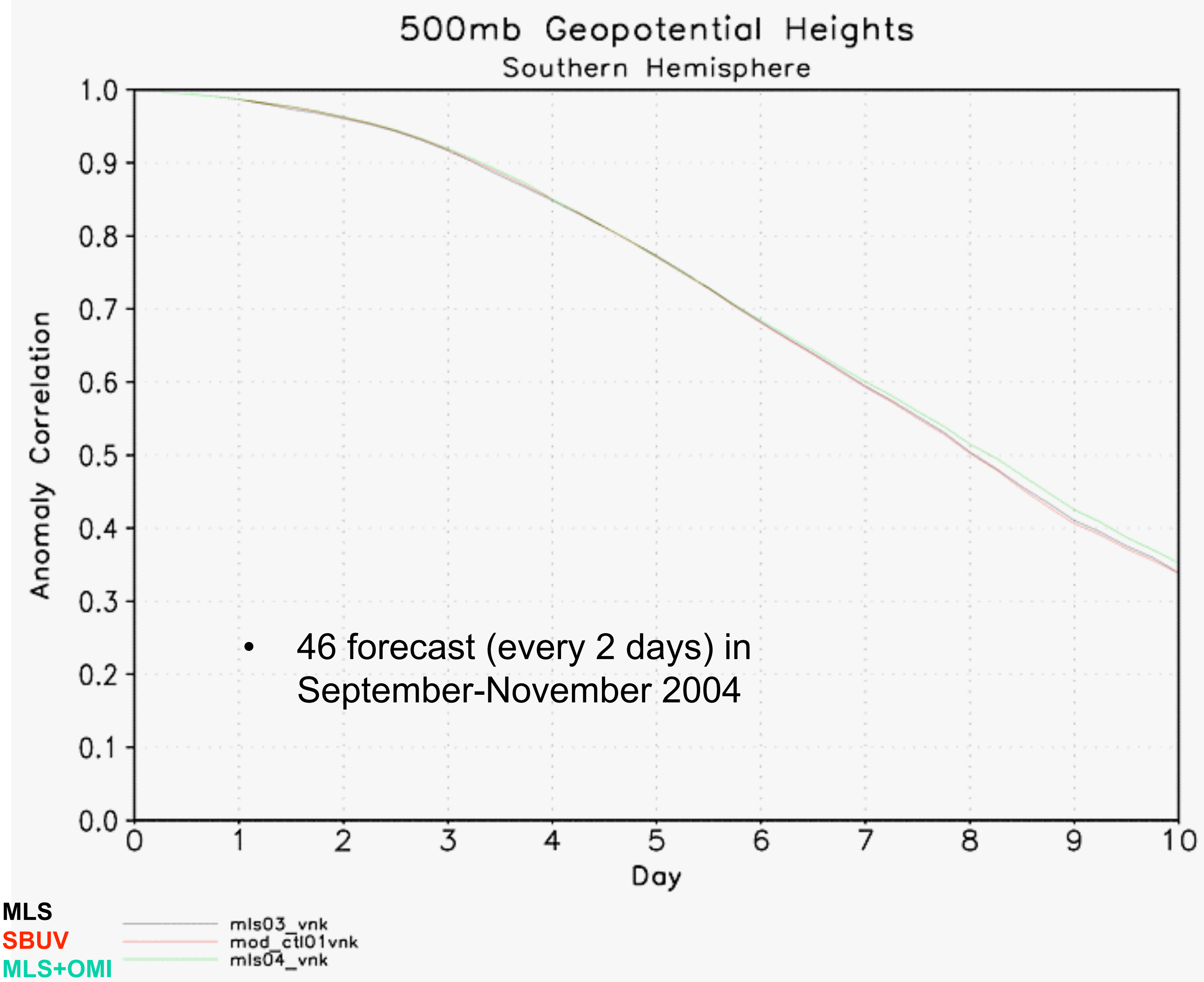
▲ NOAA 16 SBUV

◆ MLS

Zonal mean ozone 9/30/2004 00UTC



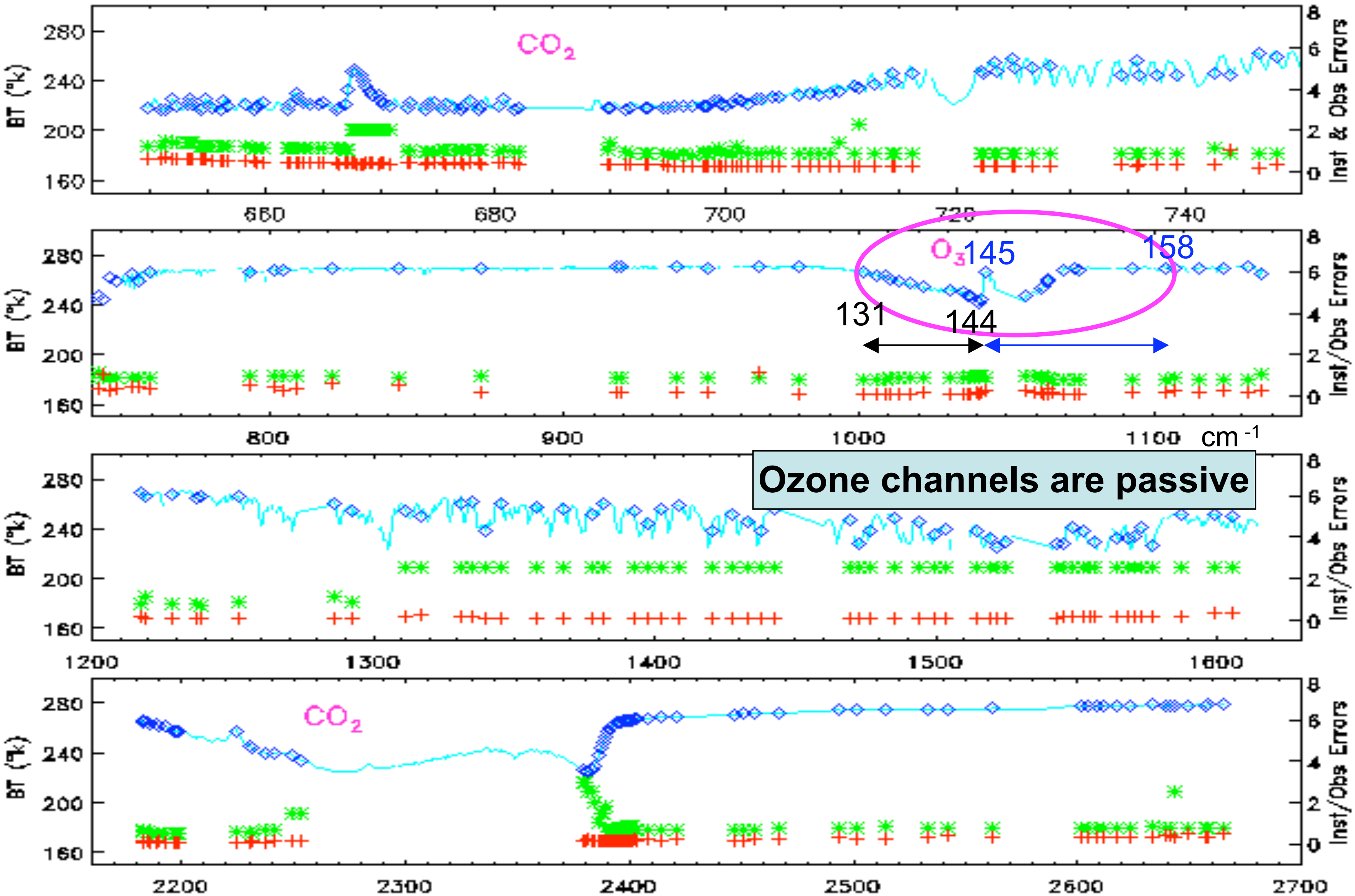
Forecast skill



- 46 forecast (every 2 days) in September-November 2004

MLS
SBUV
MLS+OMI

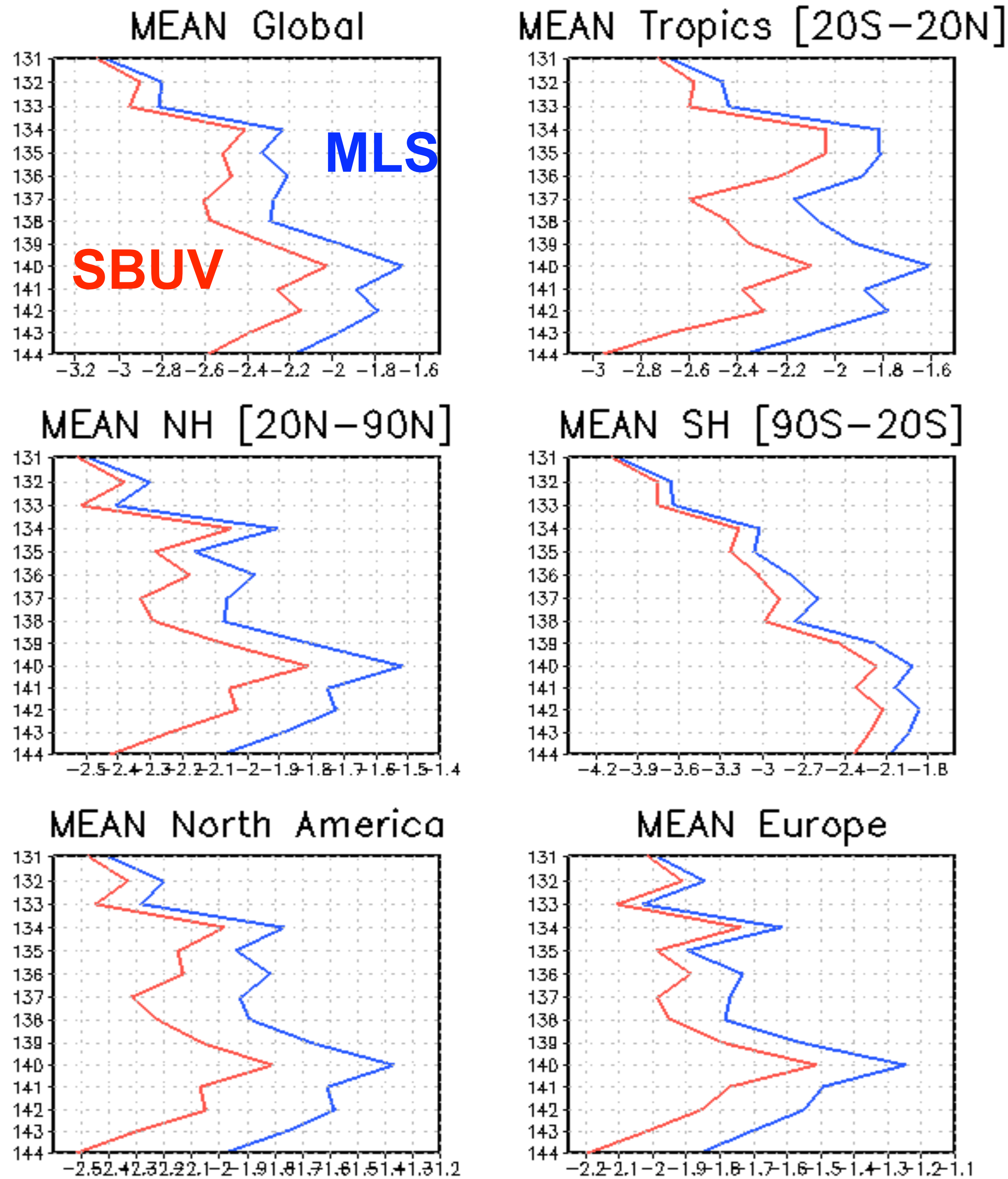
AIRS channel errors and selection



◇ 281 channels + instrument errors * observation errors

AIRS O-A mean

- AIRS observation-minus-analysis (O-A) residuals for September 2004
- Mean for ozone channels 131-144 (1001.4 - 1041.1 cm^{-1})
- Smaller bias with MLS, especially in channels more sensitive to ozone (e.g. 144)



MERRA

http://gmao.gsfc.nasa.gov/merra/

MERRA System

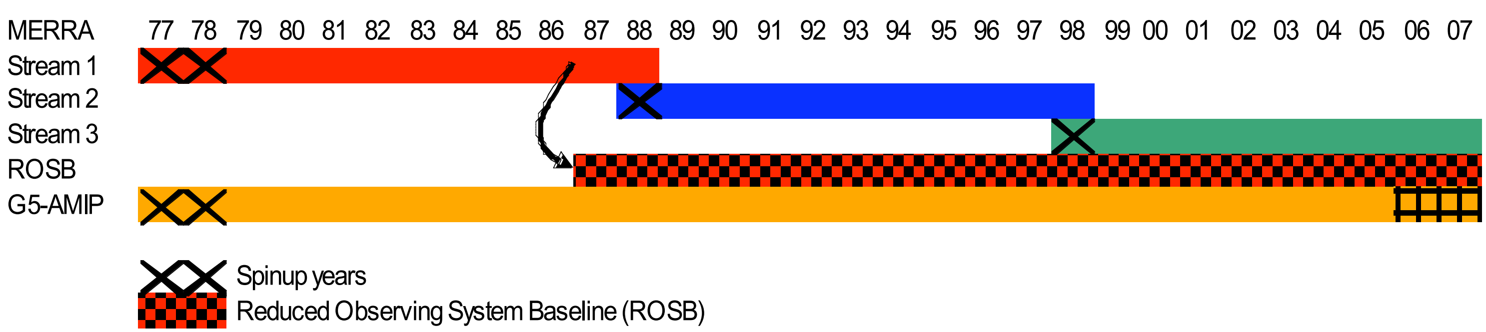
1/2° × 2/3° × 72L to .01 mb
1979-present
GSI Analysis with IAU
Parallel AMIP run

EMPHASIS ON WATER CYCLE

- Global Precipitation, Evaporation, Land Hydrology, Cloud parameters and TPW

GLOBAL HEAT AND WATER BUDGETS FOR ALL PROCESSES

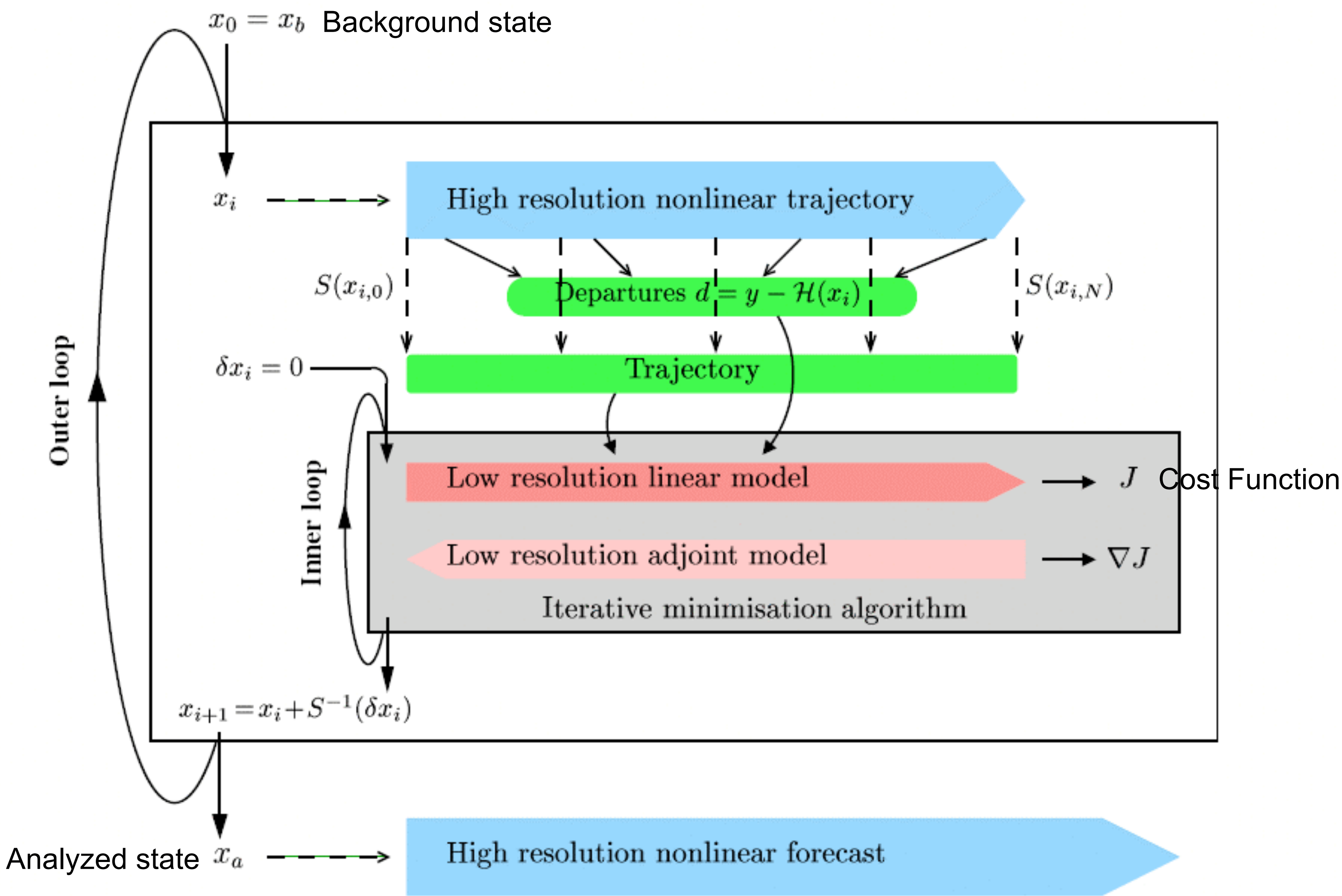
DIURNAL CYCLE FROM HOURLY 2-D FIELDS



4dVAR with GEOS-5

Yannick Tremolet and Ricardo Todling

The next System - 4D-VAR



From ECMWF

Progress in 4D-VAR Development (Tremolet & Todling)

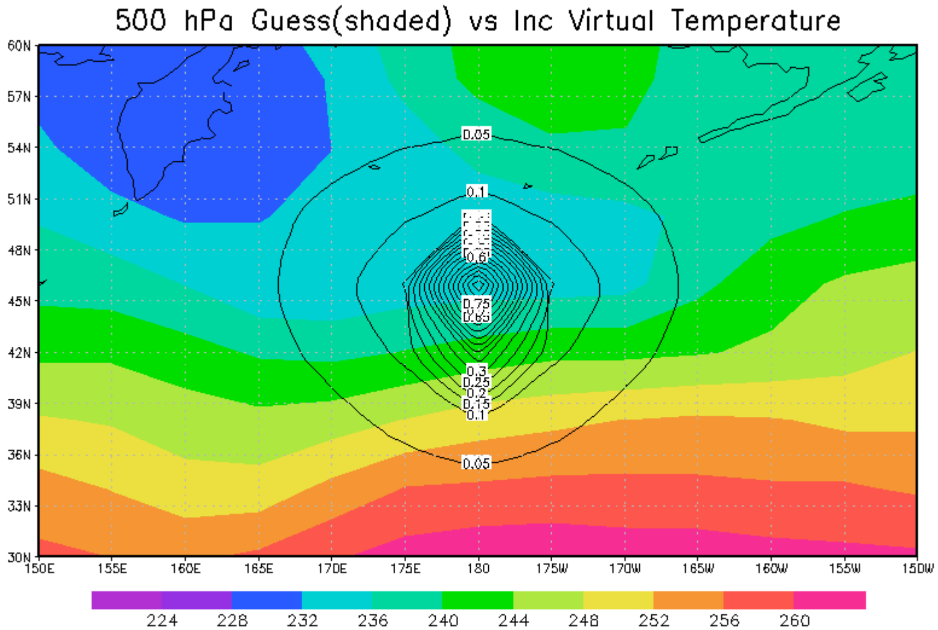
1. Trajectory Model: GEOS-5 with full physics

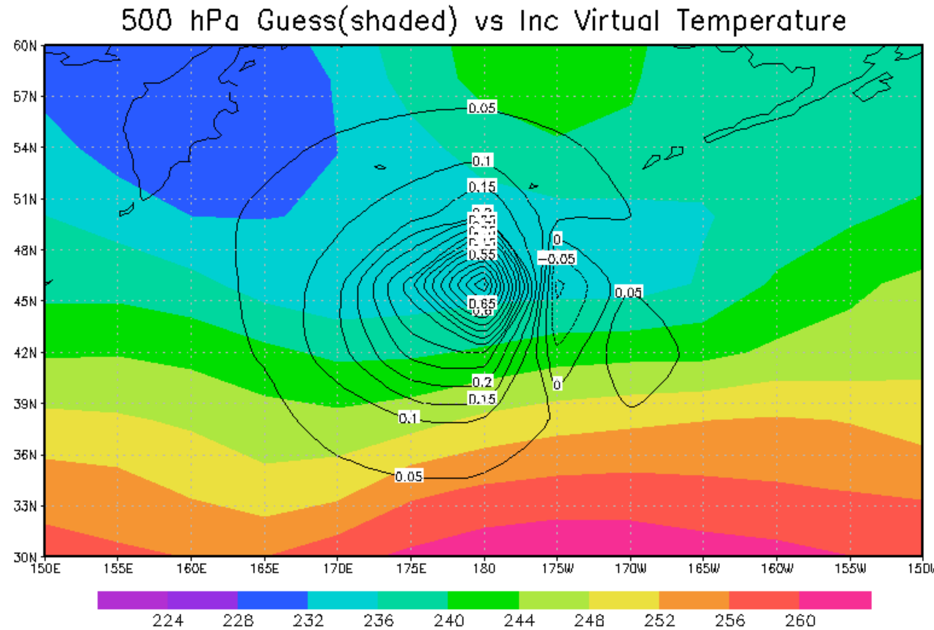
2. Model Adjoint: FV core with simple physics

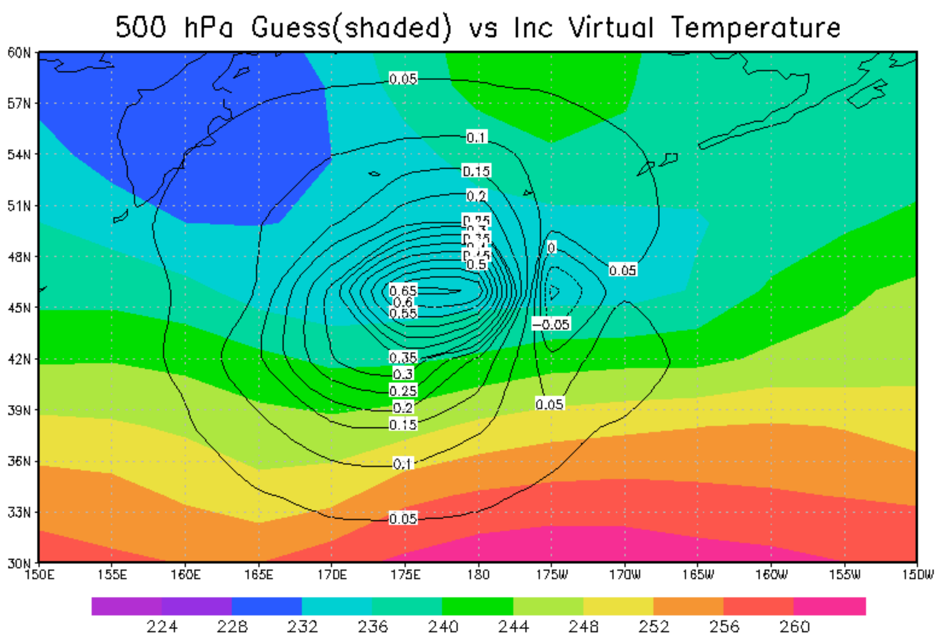
3. Extension of GSI components for 4D-VAR

- Observation windowing flexibility
- Observation handling (higher temporal-resolution bins)
- Computation of time-dependent departures (OmF’s)
- Preliminary version of model-analysis interface
- Options for minimization algorithm

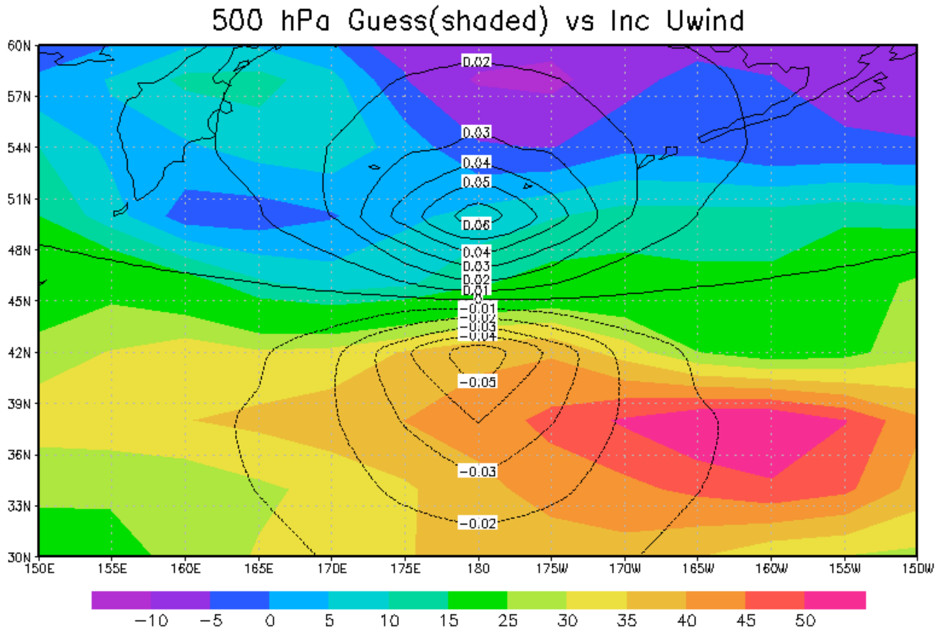
4. Fine ⇔ Coarse mappings: ESMF

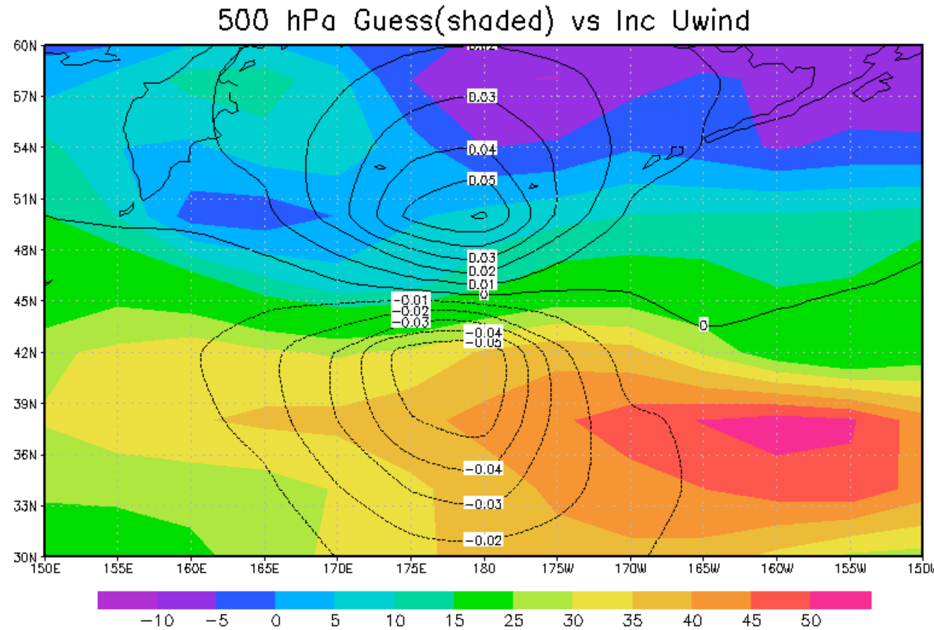


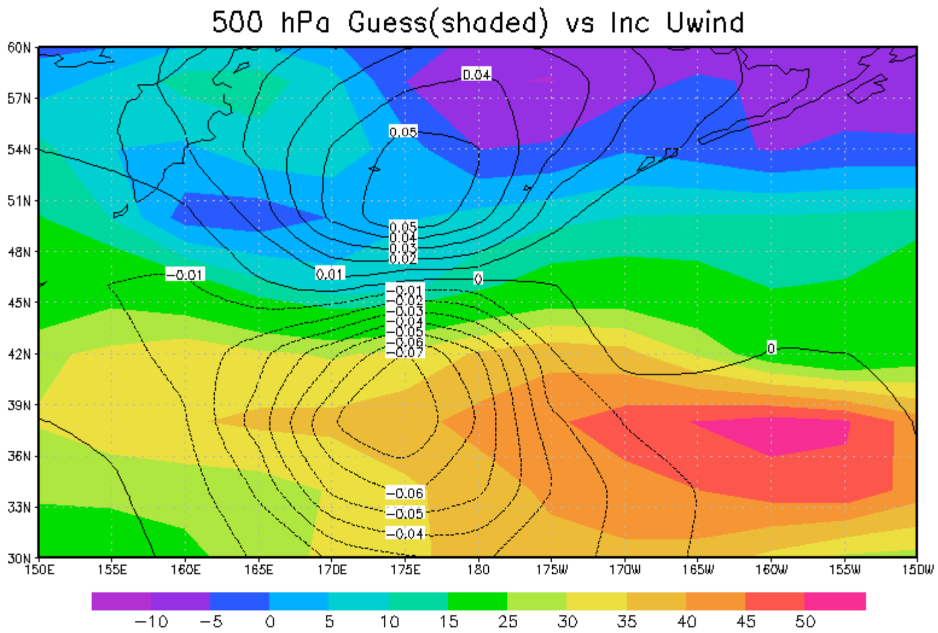




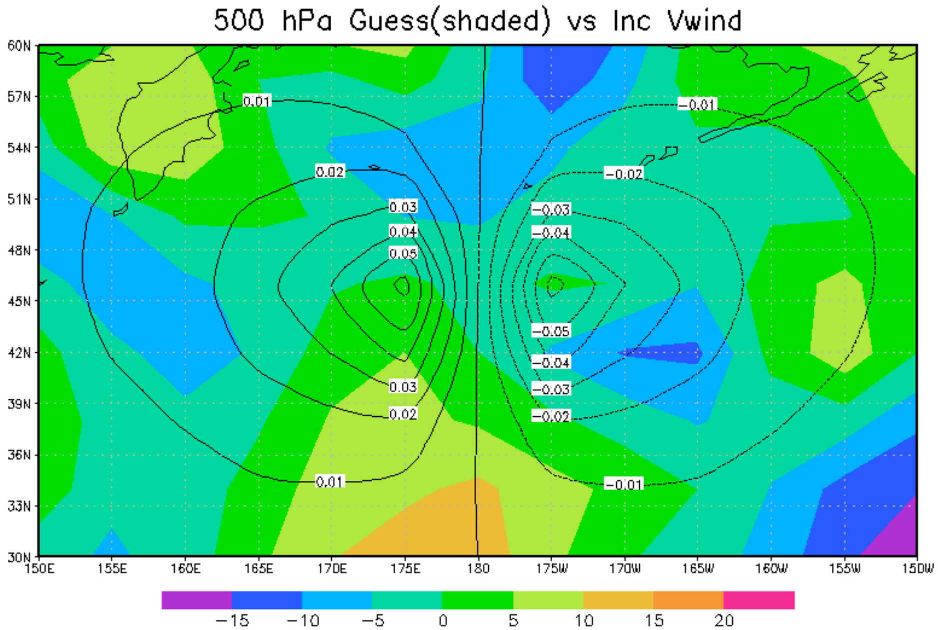
- 500 hPa Temperature Increment (cint=.05 K) at start-time for 1 K Tob (1 K ob error) at 45N 180E
- @ t-2.9, t=0, t+2.9 hrs respectively.

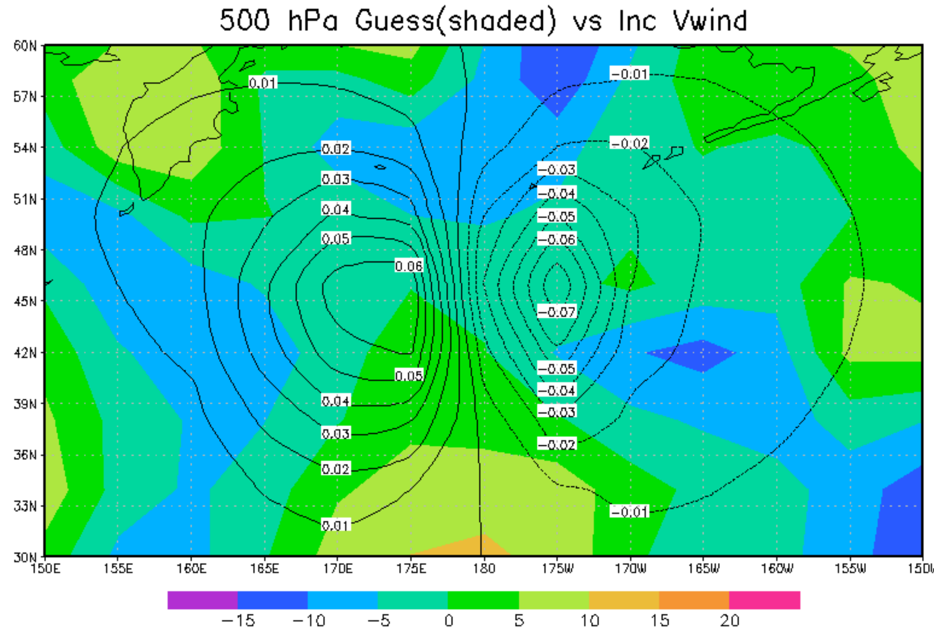


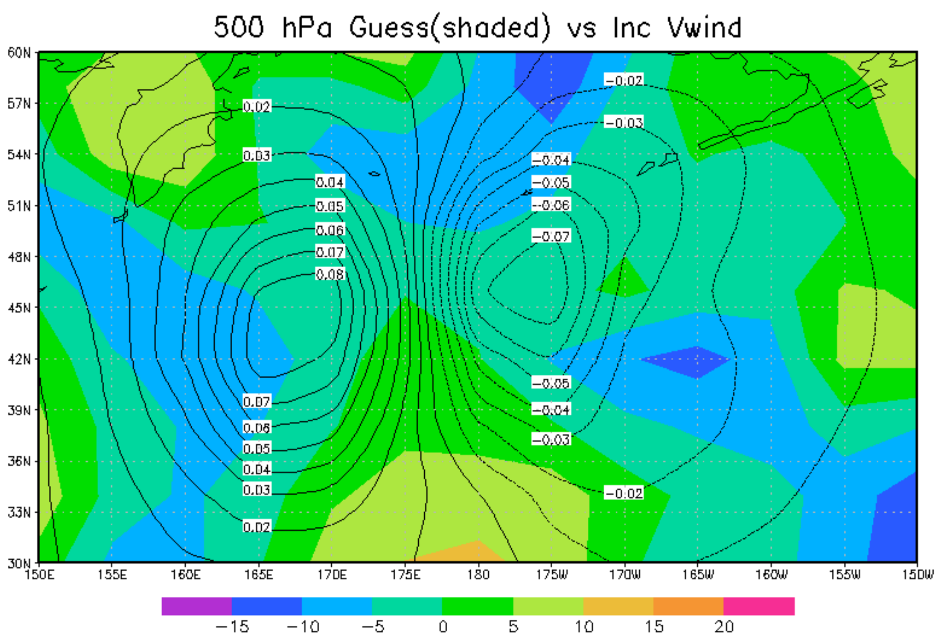




- 500 hPa Uwnd Increment (cint=.01 m/s) at start-time for 1 K Tob (1 K ob error) at 45N 180E
- @ t-2.9, t=0, t+2.9 hrs respectively.





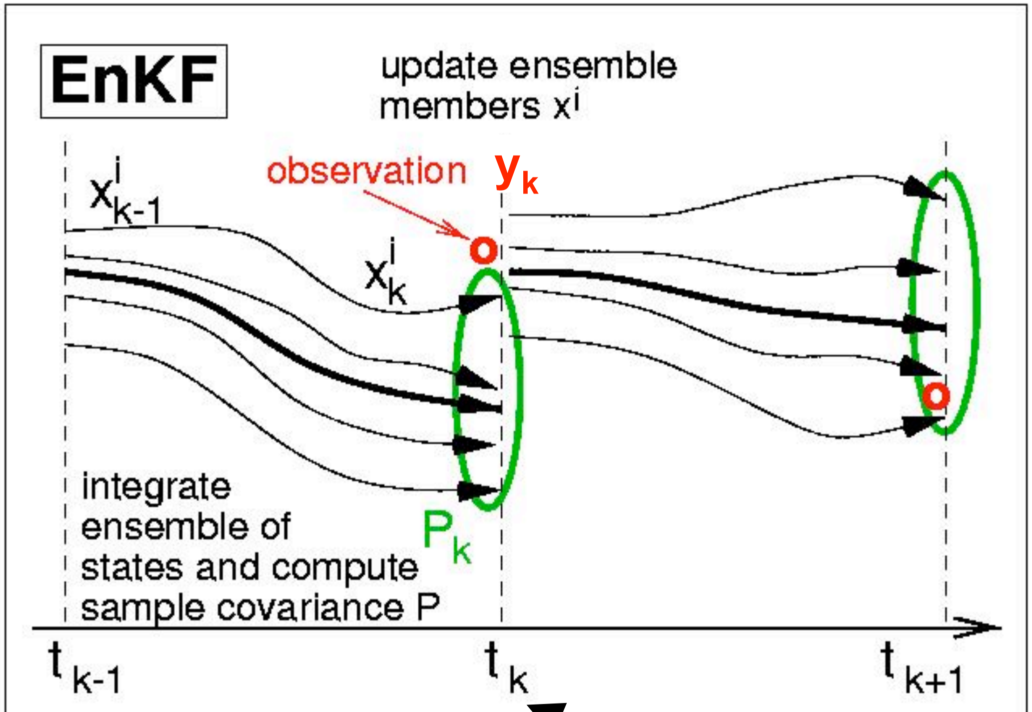


- 500 hPa Vwnd Increment (cint=.01 m/s) at start-time for 1 K Tob (1 K ob error) at 45N 180E
- @ t-2.9, t=0, t+2.9 hrs respectively.

Land Surface Data Assimilation

Rolf Reichle and Randy Koster

Soil moisture assimilation



$\mathbf{x_k}^i$ state vector (eg soil moisture)

$\mathbf{P_k}$ state error covariance

$\mathbf{R_k}$ observation error covariance

Propagation $\mathbf{t_{k-1}}$ to $\mathbf{t_k}$:

$$\mathbf{x_k^{i-} = f(x_{k-1}^{i+}) + w_k^i}$$

w = model error

Update at $\mathbf{t_k}$:

$$\mathbf{x_k^{i+} = x_k^{i-} + K_k(y_k^i - x_k^{i-})}$$

for each ensemble member i=1…N

$$\mathbf{K_k = P_k (P_k + R_k)^{-1}}$$

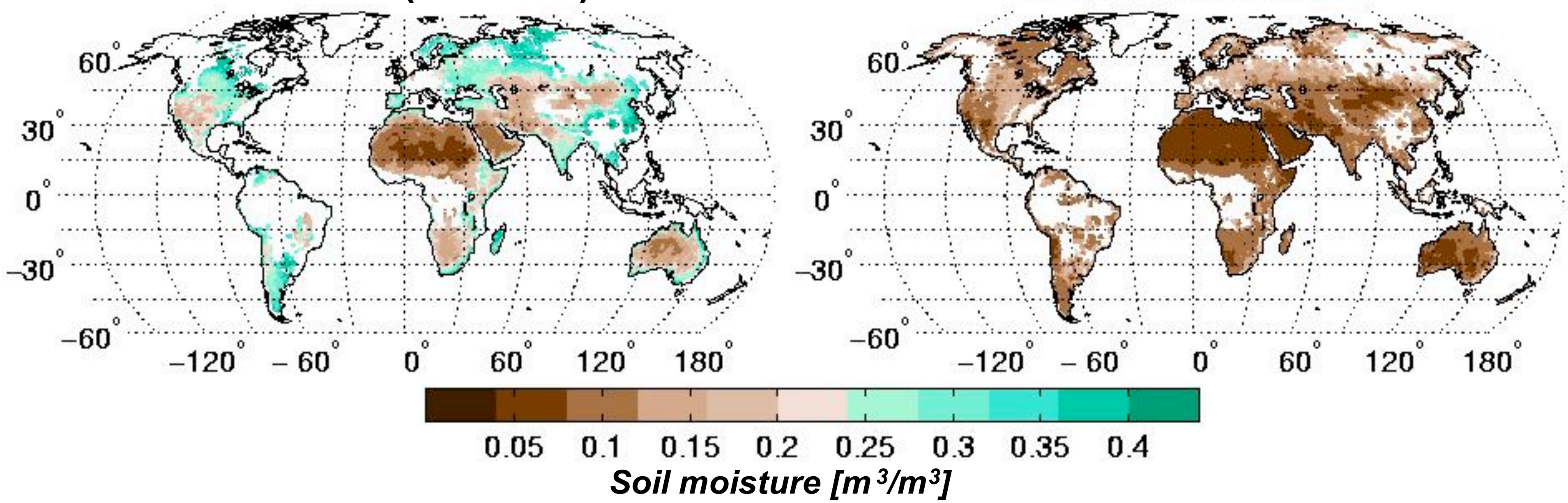
with $\mathbf{P_k}$ computed from ensemble spread

Data sources

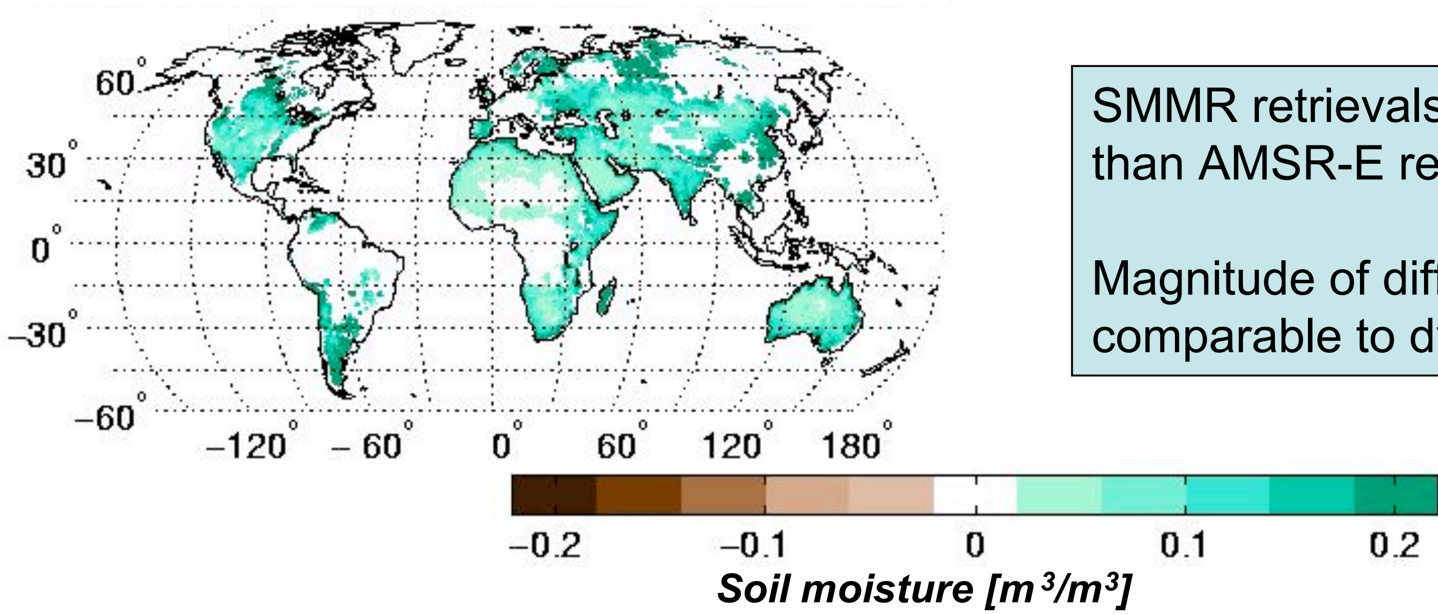
		"SMMR period" 1979-87 (~8.5 years)	"AMSR-E period" 2002-05 (~3.5 years)
Soil moisture retrievals	*Sensor*	SMMR (Nimbus 7)	AMSR-E (Aqua)
	Frequency	C-Band (6.6 GHz)	X-Band (10.7 GHz)
	Sampling depth	~1.25 cm	~1 cm
	Horiz. Resolution	~150 km	~40 km
	Equator crossing	12 am/pm	1:30 am/pm
	Algorithm	Owe et al., 2001	Njoku et al. (http://nsidc.org)
Land surface model		NASA Catchment (~0.5°)	(same w/ minor updates)
Meteorol. forcing data (obs.-based)	*Author*	Berg et al., 2005	GLDAS
	Baseline	Re-analysis (ERA-15)	NASA GEOS NWP analysis
	Observations	Monthly	Daily/pentad
	Precipitation	GPCP satellite/gauge	CMAP (5-day)
	Radiation	SRB (1983-87 only)	AGRMET daily
	Air temp./humid.	CRU	(None)
	Horiz. resolution	~2 deg	~2 deg
In situ data		GSMDB	USDA SCAN

Satellite vs. satellite bias (time avg. soil moisture)

SMMR (1979-87) **AMSR-E (2002-05)**



SMMR minus AMSR-E

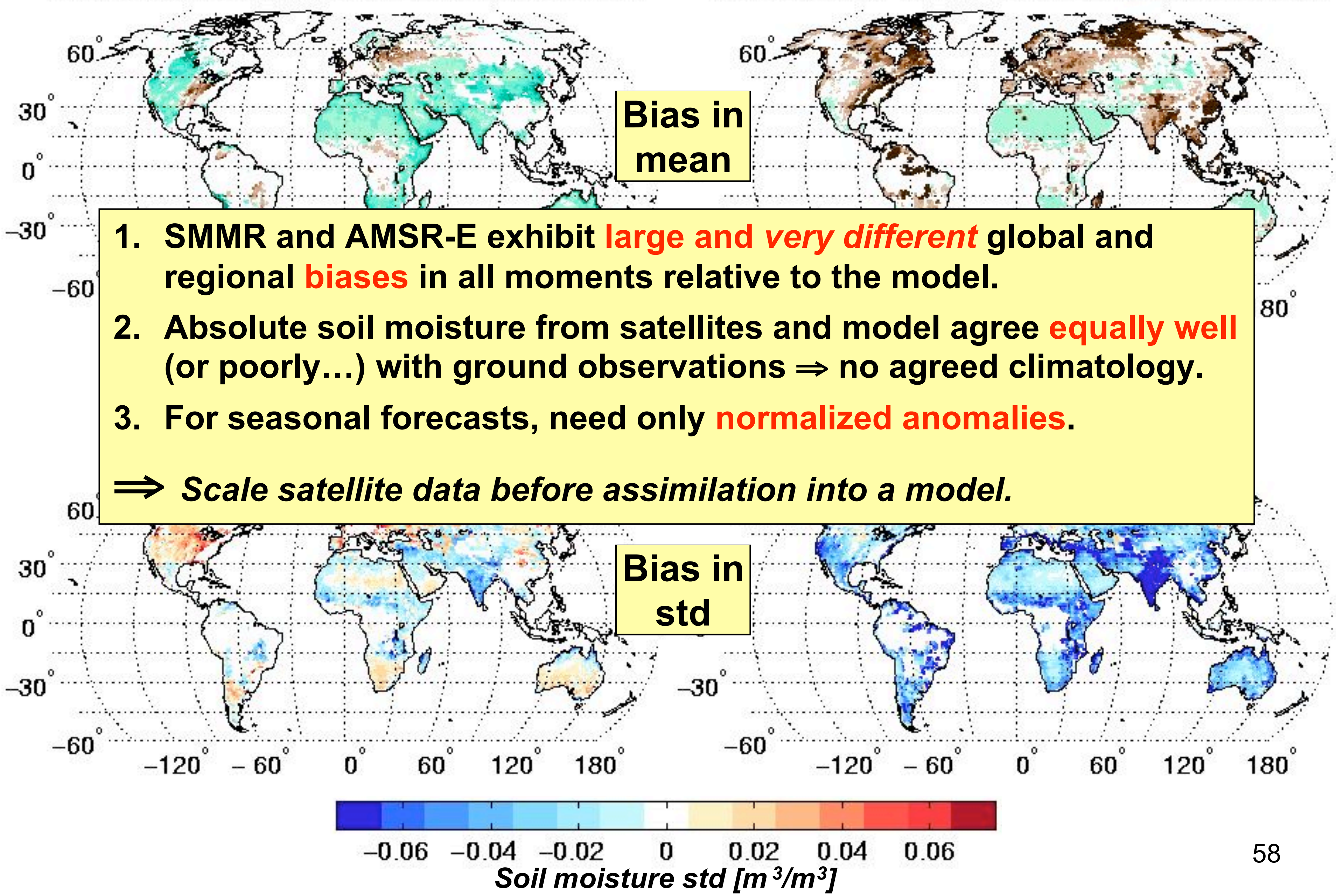


SMMR retrievals **much** wetter than AMSR-E retrievals.

Magnitude of differences comparable to dynamic range.

Satellite vs. model bias

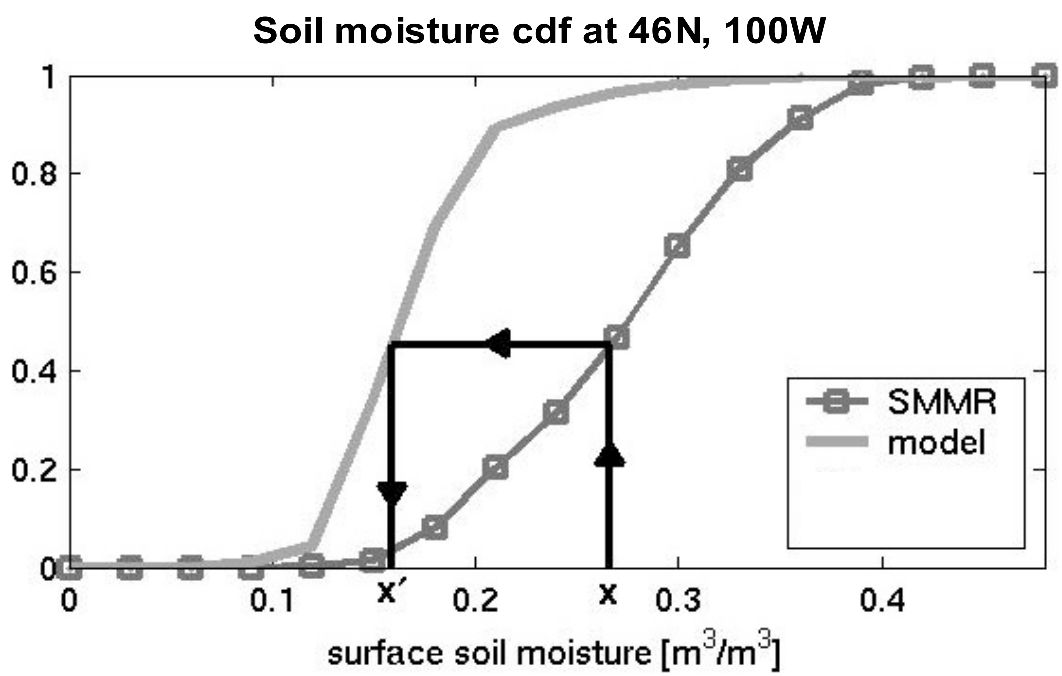
SMMR minus model (1979 -87) **AMSR-E minus model (2002 -05)**



1. **SMMR and AMSR-E exhibit large and *very different* global and regional biases in all moments relative to the model.**
2. **Absolute soil moisture from satellites and model agree equally well (or poorly…) with ground observations ⇒ no agreed climatology.**
3. **For seasonal forecasts, need only normalized anomalies.**

⟹ ***Scale satellite data before assimilation into a model.***

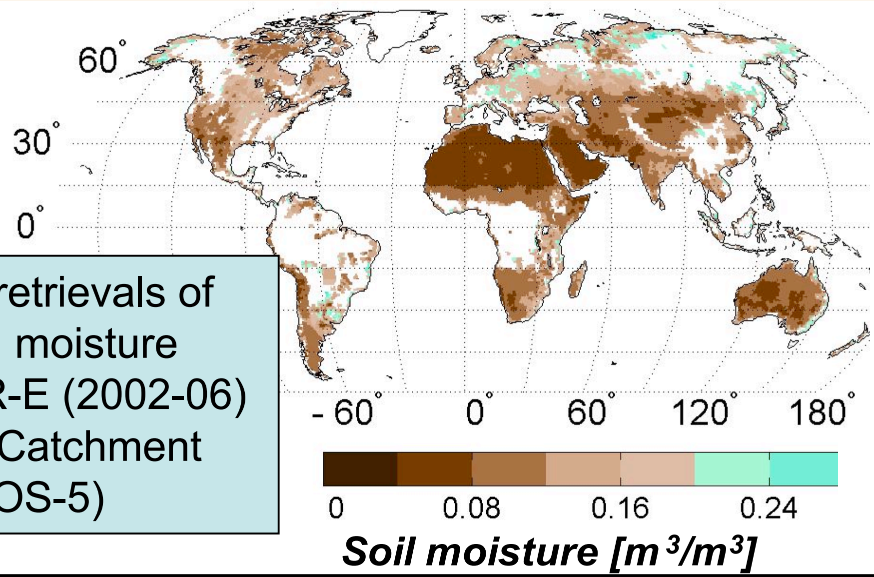
Soil moisture scaling for data assimilation



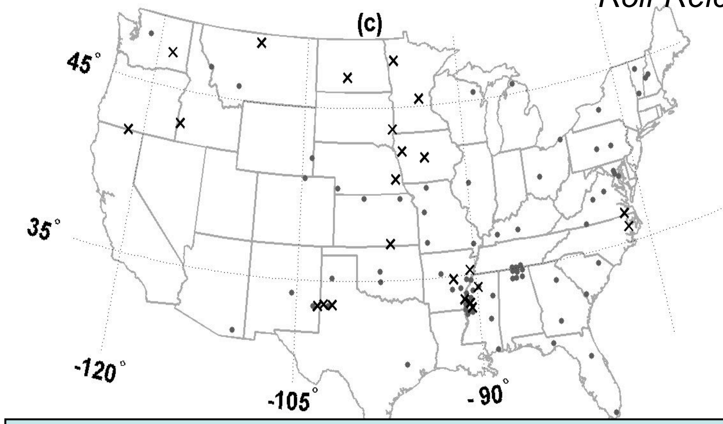
Assimilate percentiles.

Global assimilation of AMSR-E soil moisture retrievals

Rolf Reichle



Assimilate retrievals of surface soil moisture from AMSR-E (2002-06) into NASA Catchment model (GEOS-5)



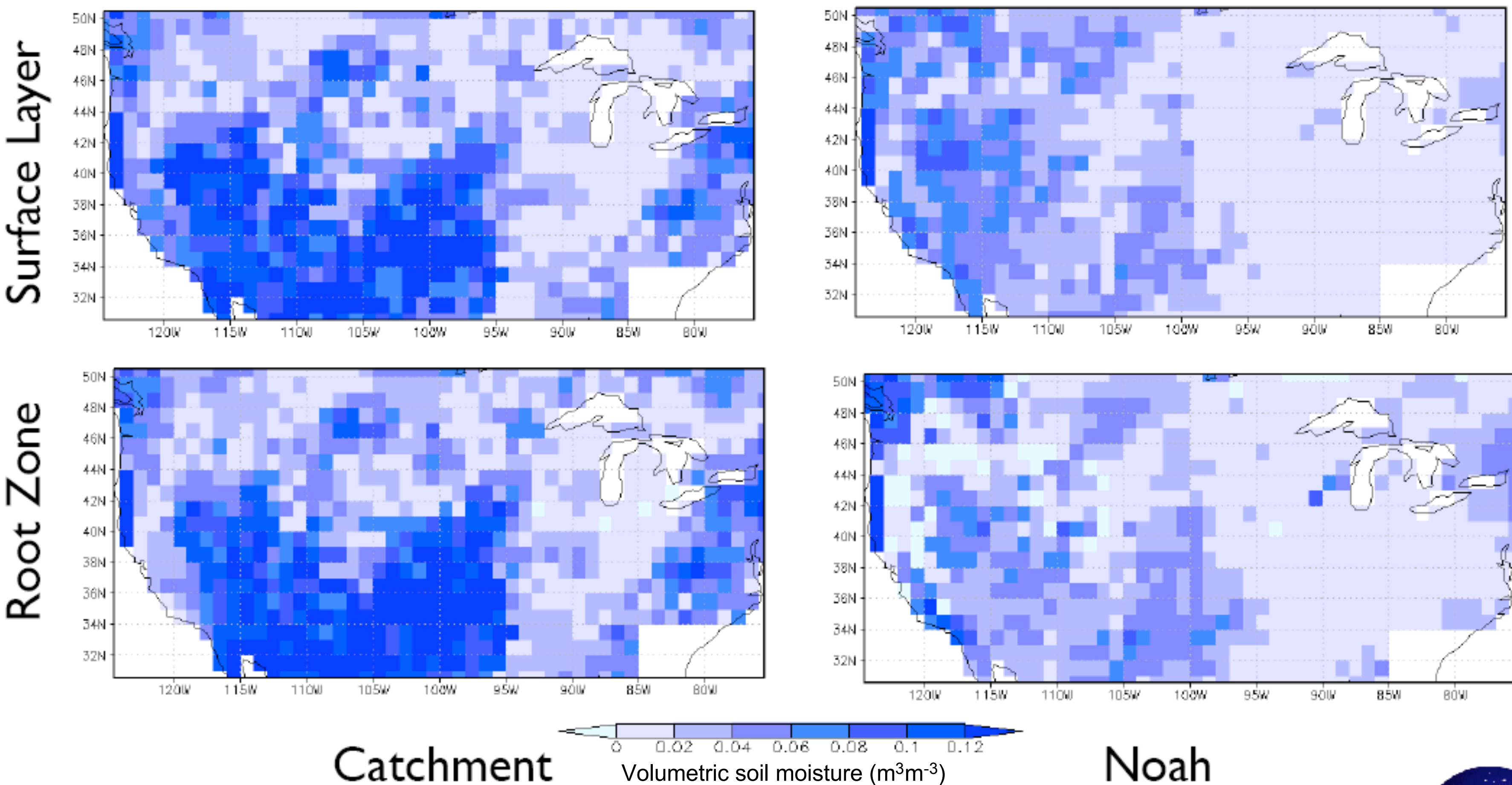
Validate with USDA SCAN stations (only 23 of 103 suitable for validation)

Reichle et al. ***JGR*, 2007**		Anomaly time series correlation coeff. with in situ data [-] (with 95% confidence interval)			Confidence levels: Improvement of assimilation over	
	N	**Satellite**	**Model**	**Assim.**	**Satellite**	**Model**
Surface soil moisture	23	**.38±.02**	**.43±.02**	**.50±.02**	**>99.99%**	**>99.99%**
Root zone soil moisture	22	**n/a**	**.40±.02**	**.46±.02**	**n/a**	**>99.99%**

Assimilation product agrees better with ground data than satellite or model alone.

Modest increase may be close to maximum possible with *imperfect* in situ data.

Improvement Metric
(RMSE(OpenLoop) - RMSE(EnKF))
for soil moisture OSSEs



Kumar, Reichle, et al. (2007), *Adv. Water Resources,* submitted.

Some references:

• Reichle, R.H., W. Crow, and C.L. Keppenne, 2007: An adaptive ensemble Kalman filter for soil moisture data assimilation, *Water Resources Res. (submitted)*

• Reichle, R. H., and R. D. Koster, 2002: Land data assimilation with the ensemble Kalman filter: Assessing model error parameters using innovations, in *Developments in Water Science—Computational Methods in Water Resources*, Vol. 47, 1387–1394, Elsevier, New York, NY.

• Reichle, R. H., and R. D. Koster, 2003: Assessing the impact of horizontal error correlations in background fields on soil moisture estimation, *J. Hydrometeorol.*, 4 (6), 1229-1242.

• Reichle, R. H., and R. D. Koster, 2004: Bias reduction in short records of satellite soil moisture, *Geophys. Res. Lett.*, 31, doi:10.1029/2004GL020938.

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GMAO - Near-term Plans

- Atmosphere:-
  - Development of 4Dvar
  - Contribute to OSSE capability
  - AIRS (QC) - CrIS
  - Ozone - GOME-2 - OMPS
  - Real-time MLS
  - MODIS Winds - VIIRS
  - CO, CO_2 (OCO)

- Land Surface:-
  - EnKF: Surface Temperature and Snow

- Ocean:-
  - MOM4: retrospective analysis for seasonal forecast
  - Surface Salinity
  - Ocean color: removing instrument biases